Physical and Chemical Studies in Lakes of the Prince Albert Park, Saskatchewan.

By D. S. Rawson
University of Saskatchewan

(*Received for publication June 5, 1935*)

CONTENTS

Introduction 227
Geography and hydrography 228
Temperature conditions 236
Dissolved oxygen 258
Carbon dioxide and hydrogen ion concentration 275
Mineral and organic analyses 278
Summary and conclusions 280

ABSTRACT

The largest of these lakes has an area of 104 sq. km. (40 sq. mi.), the deepest has a maximum of 52 and a mean depth of 21 metres. The mean annual temperature is 0.0° C. and the lakes are frozen over for six months of the year. Thermal stratification is found in six lakes each of which has a mean depth greater than 10 metres. In these lakes the thermal cycle includes the usual period of vernal circulation, summer stagnation lasting about one month and a long period of autumn circulation usually more than two months. Winter stagnation is present in an unknown degree. Two lakes with mean depths greater than 15 metres are clearly oligotrophic with no oxygen depletion at midsummer and four lakes with mean depths of from 10 to 15 metres are eutrophic and suffer from varying degrees of bottom stagnation and oxygen depletion at midsummer. Four other lakes with mean depths of less than 10 metres are not thermally stratified and are therefore free from summer stagnation. A special examination of the near bottom layer in Waskesiu lake indicates a microstratification in the lower metre which at some seasons has a decline in oxygen equal to that in the thermocline. Brief discussions are included of the dissolved carbon dioxide, hydrogen ion concentration, mineral and organic constituents of the water.

INTRODUCTION

A study of the physical and chemical conditions in lakes of the Prince Albert National park has been made in the years 1928-34, special consideration being given to the larger lakes. Since this is regarded as the first of a series of papers dealing with the scientific aspects of a limnobiological survey, it is appropriate that the nature of, and the reasons for the investigation should be recorded.

The Prince Albert National park was established in Saskatchewan in 1927. It includes about 5200 sq. km. (2000 sq. mi.) of lake and forest lands in the exact centre of the province and its flora and fauna indicate it as being in the heart of the Canadian life zone. Like the other national parks of Canada it is a recreational preserve in which the forest and game are protected and the fishing carefully supervised.

The need for a thorough limnobiological survey, as a basis for the conservation and improvement of game fishing in the park was fully recognized by authorities of the Department of the Interior and the Fish Cultural Branch at Ottawa, with the result that in 1928 the writer began such a survey under the auspices of the Biological Board of Canada. In 1931 the Board found it necessary to discontinue its financial support and since that time the University of Saskatchewan has financed the investigation.

Although this is the first scientific paper of the series, excepting Rempel, *J. Biol. Bd. Can.* **2** (*2*) *1936*, it should be mentioned that the practical aspect of the game fish situation has been the subject of several detailed reports to the departments concerned and that some of the recommendations have already been acted upon.

The data which provide the material for this report include measurement and observation of depth, area, shoreline, drainage, temperatures and chemical analysis of the water. The methods used in obtaining these data are indicated under the appropriate sub-headings. The question of light penetration has not been investigated although such data are desirable in a report of this kind. Since Secchi's disc is regularly seen at depths of 5 to 8 metres and traces of colour are rarely found in these waters the question is not regarded as urgent.

In each year the work of the field party included extensive seasonal observations on a few of the more important bodies of water to provide a continuous yearly record and a less intensive examination of a few additional lakes in the area. At the end of six years the data were thoroughly analysed and the seventh season provided opportunity for testing conclusions and rounding out the study.

The writer is pleased to acknowledge the generous co-operation of the park staff throughout the investigation. Thanks are also due to Mr. J. G. Rempel for assistance in the field work and to Prof. C. Juday of Wisconsin who provided unpublished data and who has criticised the manuscript. In the collection of comparative data we have had the generous cooperation and advice of Dr. K. M. Strøm of Oslo, Dr. H. Untermohl of Plön and Dr. C. Wesenberg-Lund of Hillerød.

GEOGRAPHY AND HYDROGRAPHY

Physical Features of the Park Area

It has been indicated above that the park is centrally located in the province (lat. 54° N. and long. 106° W.) and that the country is typical of the Canadian life zone. A more detailed description is necessary as an indication of the environment of the lakes to be discussed.

The area is mostly rolling or hilly with altitudes ranging from 503 m. (1650 ft.) near Montreal lake on the northeast boundary to 746 m. (2450 ft.) southwest of Waskesiu lake. In the latter region a large area is found above the 700 m. (2300 ft.) contour. The last column of table I indicates that most of the lakes lie between elevations of 518 and 541 m. (1700 and 1775 ft.). The central and western parts are rugged with many hills 30 to 90 m. (100 to 300 ft.) high while the eastern part is an area of low relief with extensive muskegs.

The forest cover is in most cases dense. The virgin forest appears to have been mostly coniferous, with white spruce dominant, but it is now represented by scattered stands of white spruce and balsam fir. Black spruce and tamarack are found in the wet areas and jackpine in the lighter soil. The greater part of the park area has been burned over at various times and in such sections the aspen poplar abounds. The paper birch is widespread and abundant, the balsam poplar is found chiefly around the lake margins and in the large muskeg areas two species of alder are present.

The substrate is essentially a deep glacial drift with morainic hills and ridges interspersed with smaller areas of outwash. Extensive ridges of sand or gravel outwash are usually covered with open stands of jackpine. The soil exhibits a typical forest profile with a thin layer of humus overlying a grey leached layer on the hills and in the valleys a rich peaty loam verging into the muskeg.

Boulders are prominent in the stream beds and along the lake shores, about two-thirds of the latter being of a rocky nature. No rock outcrop is found in

TABLE I. Dimensions and conformation of the chief lakes studied.

Lake	Area sq.km. (sq.mi.)	Length approx. km. (mi.)	Width approx. km. (mi.)	Depth (metres) Max.	Depth (metres) Mean	Volume Millions cubic metres	Shore-line length km. (mi.)	Shore development	Elevation m. (ft.)
Crean	104 (40)	14.0 (9.0)	7.2 (4.5)	27	11.8	1220	80.5 (49.9)	2.2	525 (1721)
Waskesiu	70 (27)	26.0(16.0)	4.8 (3.0)	24	11.1	770	75.5 (47.0)	2.6	530 (1740)
Kingsmere	47 (18)	10.0 (6.0)	4.8 (3.0)	47	21.2	990	32.5 (20.2)	1.3	537 (1760)
Bittern	31 (12)	13.0 (8.0)	3.2 (2.0)	5	2.3	71	35.5 (22.0)	1.8	510 (1672)
Lavallee	24 (9.3)	7.0 (7.0)	2.4 (1.5)	14	6.5	157	48.0 (29.8)	2.7	542 (1778)
Helkett	10.1(3.9)	4.8 (3.0)	2.7 (1.7)	52	10.6	107	18.8 (11.7)	1.7	-
Wassegam	9.1(3.5)	4.8 (3.0)	2.4 (1.5)	35	15.5	140	13.2 (8.3)	1.2	-
Clearsand	8.8(3.4)	6.0 (3.7)	1.9 (1.2)	2.8	1.6	14	16.3 (10.1)	1.5	507 (1662)
Namekus	7.3(2.8)	3.5 (2.2)	2.4 (1.5)	27	11.9	83	10.9 (6.8)	1.1	524 (1719)
Tibiska	7.3(2.8)	4.0 (2.5)	2.4 (1.5)	13.5	5.5	40	13.0 (8.1)	1.4	-

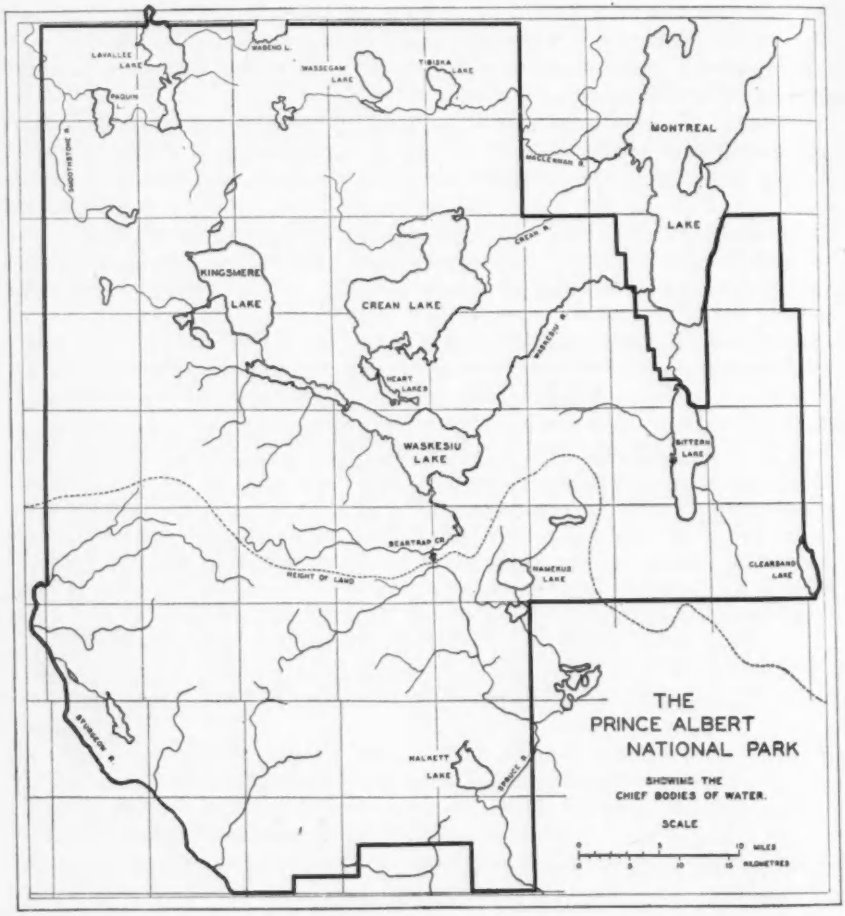
the park region, the nearest being about 129 km. (80 mi.) north at Lac La Ronge where strata of Devonian limestone overlie the Precambrian rocks.

The general direction of movement in the Pleistocene ice sheet which covered this area was to the southwest, yet the long axes of the lake basins in the park and in the area immediately westward tend to lie in a north and northwest direction. It is apparent from this and from other considerations that the local ice activities were of a complex nature needful of further study. In the higher central and western parts of the park the lake basins are of a type usually associated with recessional moraine country, while the general topography of the eastern part suggests that Montreal and Bittern lakes may be remnants of a much larger lake which once covered that area.

LOCATION OF LAKES AND DRAINAGE

The park includes a very large number of lakes, four of which, Crean, Waskesiu, Kingsmere and Bittern, might be described as large, having areas

of 31 to 104 sq. km. (12 to 40 sq. mi.). Eleven lakes of intermediate size have areas of 2.6 to 26 sq. km. (1 to 10 sq. mi.) and more than 450 small lakes are less than 2.6 sq. km. (1 sq. mi.) in area, excluding those less than 0.65 km. (one-



PRINCE ALBERT PARK.

FIGURE 1. The Prince Albert National Park showing the chief lakes, the height of land and drainage areas.

quarter of a mile) in diameter. The locations of the large and intermediate lakes are indicated in figure 1.

The height of land indicated in figure 1 divides the park into a northern watershed which drains into the Churchill river and a southern portion draining into the North Saskatchewan. The northern portion is

about 3500 sq. km. (1350 sq. mi.) in area and includes all the large lakes. Approximately 388 sq. km. (150 sq. mi.) of this drains into Lavallee and Paquin lakes and on through Smoothstone lake and river into Snake lake in the Churchill valley. The remainder, 3110 sq. km. (1200 sq. mi.) drains through Montreal lake and river to Lac la Ronge on the Churchill river. Of the southern portion an area of about 648 sq. km. (250 sq. mi.) at the west drains into the Sturgeon river, the remainder 777 sq. km. (300 sq. mi.) into the Spruce river, both of which empty into the North Saskatchewan.

Morphometry of the Chief Lakes

The dimensions and the conformation of the chief lakes studied are presented in a brief form in table I and a comparison of the depth distribution in five of the lakes in table II.

The methods used in obtaining these data are as follows. Areas are determined with a planimeter using maps which were plotted on a scale of not less than one centimetre to 0.635 kilometres (one inch to a mile). Depth was measured with sounding lines of tarred cotton graduated in metres and calibrated at regular intervals to eliminate error due to stretching or shrinkage. The location of soundings was accomplished by means of sighting from and to shore, by timing an outboard motor and by the use of bearings taken with a prismatic compass. The number of soundings in the larger lakes ranged from 900 in Waskesiu to 130 in Halkett. For these lakes contours were drawn at five metre intervals and mean depth was calculated on a basis of the relative areas of the depth zones. In Lavallee, Wassegam, Namekus and Tibiska lakes a smaller number of soundings, 25 to 60, were made. The mean depth was determined very roughly in these cases by drawing approximate five and ten metre contours. It is probable that in these lakes the maximum depths recorded are somewhat less than the true maximum. Volume, as recorded, is the product of mean depth and area. The length of shoreline was measured from the maps used for the determination of area, that is, on scales not less than one centimetre to 0.635 kilometres (one inch to a mile). Shore development is defined as the ratio of actual shore length to the perimeter of a circle of area equal to that of the lake. The percentage areas at various depths and the relative volumes of the separate strata as presented in table II are calculated directly from the aforementioned contour maps. Lake levels listed in table I are from the Geodetic Survey.

The morphometrical data for the lakes under consideration may be discussed as follows:

Crean lake is the largest (104 sq. km., 40 sq. mi.) of the lakes in the Park. The shallow water zone (0 to 5 m.) is unusually large, including 32.6 per cent of the total area of the lake. The remainder of the lake slopes down gradually, as may be seen in table II, to a maximum depth of 27 m. The large shallow area resulted in a mean depth of only 11.8 m. although 23 per cent of the lake is more than 20 m. in depth. An irregular shoreline is indicated by its shore development of 2.2. A number of shallow protected bays are found along the south shore and one large shallow bay, Moose bay, is at the north. The water

level is 525 m. (1721 ft.) which is 5 m. (19 ft.) below that of Waskesiu lake. It has been proposed that a 274 m. (300 yd.) canal be cut from Waskesiu to the Heart lakes and a dam placed at the outlet of Waskesiu to divert part of the flow through Crean lake, Crean creek, and the Burntwood river. This would make possible a water route to Montreal lake through Crean lake and the Crean river, eliminating the difficult Waskesiu river route which is now used.

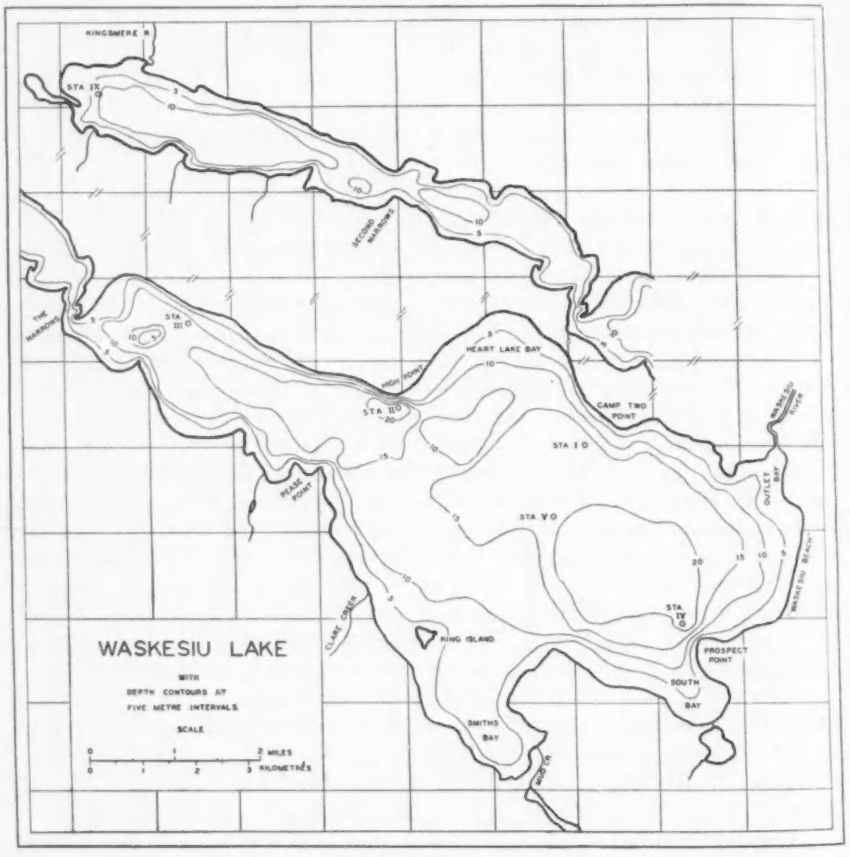


FIGURE 2. Waskesiu lake showing depth contours at five metre intervals and the location of stations.

Waskesiu is the second largest of the lakes and as indicated above, was the subject of the most intensive study. Figure 2 indicates the depth contours for Waskesiu lake at 5 m. intervals as well as the location of the chief stations at which limnological observations were made. For convenience in mapping the upper part of the lake is indicated as having been shifted to the right (see figure 1). The depth contours were drawn with the aid of 900 determinations of

depth. Although its maximum and mean depths are of the same order as those of Crean lake an examination of table II will show that the lakes are really quite unlike. In Waskesiu the shallow water (0 to 5 m.) is less than 20 per cent of the total area and the largest depth zone is that between 10 and 15 m. which includes 30.7 per cent of the whole. Thus while Crean lake had a large area of shallow water and a second large area in which the depth is more than 20 m., Waskesiu has a large area of intermediate (10 to 15 m.) depth and only 7.5 per cent of its area more than 20 m. deep. The latter difference has been found to be of great importance in the limnology of the two lakes.

The relative volumes of water to be found at various depths in the lake were needed for the calculation of mean lake temperatures and for other purposes. Making use of the data in table II as to the relative areas of the various depth zones, the volumes of the various strata were calculated and inserted in the columns marked B of the same table. Although the method used in this calculation assumes a uniform decline between successive 5 metre depth contours, it can be shown that the error involved is considerably smaller than the probable error involved in plotting the said contours.

The deepest water in Waskesiu lake is found in two depressions of the lower lake, one off Prospect point with a maximum depth of 24 m. and a smaller one off Big point with a depth of 21 m. These regions are approximately 6.5 km. (4 mi.) apart and separated by a large area in which the depth is from 10 to 15 m. Stations IV and II respectively were located in these depressions for limnological observation.

The shoreline is long, only 5 km. (3 mi.) less than Crean, which is a much larger lake, and the shore development of Waskesiu (2.6) is consequently higher. This is due not so much to irregularity of the shoreline as to the great elongation of one arm of the lake. The lower basin is about 7.2 km. (4.5 mi.) in diameter and a narrow arm extends from this 16 km. (10 mi.) to the northwest.

The water level of Waskesiu lake is given by the Geodetic Survey as 530 m. (1740 ft.) which is 40 m. (131 ft.) above that of Montreal lake. This fall is apparent in the large number of rapids in the outlet, Waskesiu river. The water level in Waskesiu and in the other lakes of the park varies considerably from year to year and at different seasons of the same year. The maximum variation between low and high water in recent years is 0.64 m. (2.1 ft.). The ice level usually lies within the lower 0.3 m. (1.0 feet) of this range and the spring floods cause a rapid rise above this level. Thus in 1933 the spring run-off resulted in a sudden rise of 0.61 m. (2.0 ft.). The level usually decreases to a minimum in late summer and autumn. In comparison with many other lakes a variation of 0.64 m. (2.1 ft.) is comparatively low. In this connection it should be mentioned that the mean annual precipitation is about 16 inches (40 cm.). Of this amount about 75 per cent falls during the months of June to September and the remaining 25 per cent falls chiefly as snow.

From an examination of figure 2 it is apparent that Waskesiu lake is almost divided at the Narrows, a neck of water about 94 m. (125 yd.) in width. It was frequently evident that both physically and biologically these parts could very well be considered as individual lakes. In this respect Upper and Lower Waskesiu might be compared as follows:

	Upper Waskesiu	Lower Waskesiu
Area	11.1 sq. km. (4.3 sq. mi.)	59.0 sq. km. (22.7 sq. mi.)
Length approx	10.4 km. (6.5 mi.)	14.7 km. (9.2 mi.)
Width approx	1.1 km. (0.7 mi.)	7.3 km. (4.5 mi.)
Depth, max	15.0 m.	24.0 m.
Depth, mean	7.8 m.	11.8 m.
Volume	84.0 cu. m. $\times 10^6$	686.0 cu. m. $\times 10^6$
Shoreline	29.0 km. (18 mi.)	46.7 km. (29 mi.)
Shore development	2.4	1.7

Upper Waskesiu is seen to be a small, narrow and shallow lake. Lower Waskesiu is a lake of moderate size and depth and with very little protected shore line.

Kingsmere lake is chiefly remarkable for its depth. Fifty-four per cent of its area is more than 20 m. in depth and of this only a small area is deeper than 40 metres as may be seen from table II. As a result of these large deep water areas the volume of the lake is proportionately great. Although the area of Kingsmere lake is 33 per cent less than Waskesiu its volume is greater than that of Waskesiu by 23 per cent, a situation of special significance in the limnology of the lakes concerned.

TABLE II. Relative areas of depth zones "A" and relative volumes of strata "B", in five lakes expressed as percentages of total area and volume.

Depths in metres	Percentages									
	Crean		Waskesiu		Kingsmere		Bittern		Helkett	
	A	B	A	B	A	B	A	B	A	B
0 - 5	32.6	36	19.1	41	16.9	22	100	100	49.4	37
5 - 10	17.0	25	23.4	31	11.0	19	-		13.9	21
10 - 15	17.0	17	30.7	19	9.0	16	-		13.1	15
15 - 20	10.3	13	19.3	8	7.4	14	-		7.3	9
20 - 25	10.2	8	7.5	1	14.5	12	-		4.3	7
25 - 30	12.9	1	-		11.1	9	-		3.8	5
30 - 35	-		-		18.1	5	-		3.1	3
35 - 40	-		-		7.9	2	-		2.6	2
40 - 45	-		-		3.6	1	-		0.9	1
45 - 50	-		-		0.5	0	-		1.1	0
50 - 55	-		-		-		-		0.1	0

Bittern lake is long and very shallow with a mean depth of only 2.3 metres. It is so shallow that dense growths of rooted aquatic plants are often encountered in the central part of the lake. In many ways Bittern lake is similar to the much larger Montreal lake which lies directly north in the same depression.

Lavallee lake is also shallow with a mean depth of 6.5 m. and with a shoreline of unusual irregularity. The shore development of 2.7 is the greatest found in any of the park lakes.

Halkett lake, also known as Sandy, is less than half as great in area as any of the four lakes described above. It is, however, the deepest of any of the park lakes, having a maximum depth of 52 m. In marked contrast with Kingsmere

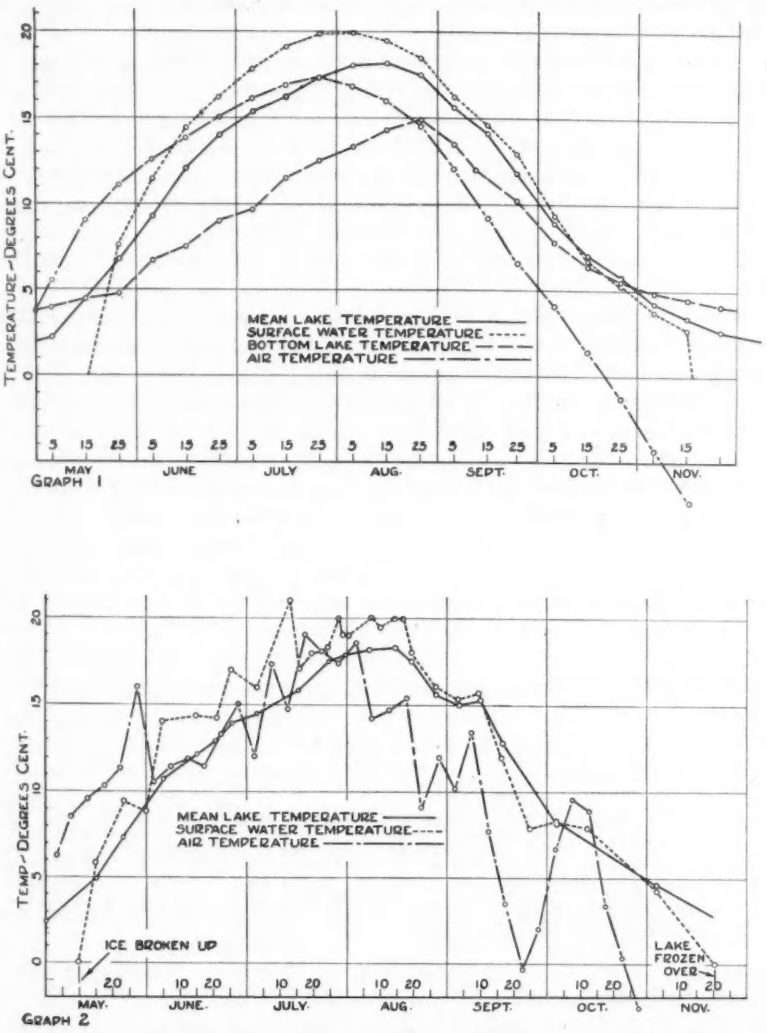


FIGURE 3. Graph 1,—Average temperature conditions in Waskesiu lake 1928-34. Graph 2,—Temperature conditions in Waskesiu lake 1934.

lake the deep water in Halkett is greatly restricted. Only 16 per cent of its area is deeper than 20 m. as compared with 54 per cent in Kingsmere. Large shallow areas toward the north and west shores contribute to the extensive (49.4 per cent) 0 to 5 m. zone.

Wassegam commonly known as Clearwater is a small deep lake. With respect to depth, shore development and fauna it resembles Kingsmere.

Clearsand lake can be readily described as a smaller counterpart of Bittern lake and even shallower than the latter. Its mean depth of 1.6 metres is its most essential characteristic.

Namekus lake is a small lake with a very regular shoreline as is indicated by its shore development of 1.1 the lowest found in any of these lakes. It is unexpectedly deep with a maximum of 27 and a mean depth of 11.9 metres, being in these respects much like Waskesiu lake. Although its area is only one-tenth that of Waskesiu it is in many ways similar to the larger lake. It is of additional interest because of its location in the Saskatchewan river drainage area.

Tibiska lake, also known as Burntwood, is shallow and quite regular in outline.

From the general survey of these lakes it appears that the mean depth is the most significant single factor in their classification. The importance of depth is not purely a matter of morphology for, as Thienemann (1927) has shown, the mean depth of a lake affects its biological organization and practically determines its trophic condition.

Making use of the data presented above and anticipating certain facts that will appear later the lakes may be grouped into morphological classes as follows:

Kingsmere and Wassegam are placed together as a distinct type, Crean representing a second type and Halkett in many respects like Crean though possessing some features of the first group. Waskesiu is placed in a division by itself with Namekus as a possible smaller relative and Lavallee, Bittern, Clearsand and Tibiska shallow lakes of a single type.

TEMPERATURE CONDITIONS

Waskesiu Lake

SURFACE TEMPERATURES

Ice covers the surface of Waskesiu lake for approximately one-half of the year. When the ice sheet has formed, its thickness increases rapidly, reaching at the end of the cooling period late in February a thickness of about 0.9 m. (3 ft.). During the period of observation the ice of Waskesiu lake has formed and broken up on the following dates:

	Ice broken up	Ice formed		Ice broken up	Ice formed
1927	May —	Nov. 13	1931	May 11	Nov. 15
1928	" 19	" 28	1932	" 10	" —
1929	" 25	" 10	1933	" 20	" 15
1930	" 18	" 20	1934	" 11	" 21

Once the main sheet of ice has broken its disappearance is very rapid. The time of freezing is less clearly marked since several sheets may form and be

broken up before the final covering is established. The dates for "ice formed" above refer to the formation of this final sheet.

Crean lake freezes and breaks up at approximately the same date as Waskesiu. Kingsmere on the other hand freezes about December 1 and has been known to remain open until December 17. The break-up is also later than in Waskesiu, the ice often remaining until May 24. Halkett lake freezes about five days earlier than Waskesiu and breaks up earlier by about the same period. Bittern lake freezes early in November and is usually open earlier than any of the other lakes.

Comparing the lakes it appears that the controlling factor in the formation and destruction of the ice sheet is the relative volume of deep water to be warmed or cooled rather than the area or volume of the lake. Thus Kingsmere with 54 per cent of its area deeper than 20 metres is the last in each year. Waskesiu and Crean represent the intermediate condition while Halkett, though deeper than Kingsmere, has a much smaller quantity of deep water and therefore changes temperature more readily than any of the former three. Bittern lake being extremely shallow responds most quickly of all to changes in temperature.

The seasonal variation in the surface temperature during the period of open water is shown in graph 1, in which a curve represents the average of surface temperatures during the seven year period. Separate graphs were drawn for each year from observations made at intervals of not greater than three days. From these curves the mean temperature was calculated at intervals of five days and plotted on graph 1. It should be noted that observations began before May 15 and continued after September 15 in only four of the seven years. For temperatures taken in October and November the writer is indebted to the Engineering Service of the Prince Albert National park.

The process of averaging seven years' data has to a large extent smoothed out the special variations to be found in any single year. The resulting curve shows a fairly smooth rise from May 16, when the ice breaks up, to a maximum of about 20° C. in the last week of July and the first week of August. From this point the temperature declines with slight irregularity until the freeze-up at November 17. The rate of warming and cooling of the lake surface is directly affected by the amount of mixing caused by winds. Since changes in the mean temperature of the lake are an indication of mixing, a curve representing seasonal variation in mean lake temperature for the seven year period is included. There is also plotted in graph 1 a curve representing the average of mean air temperatures for the same period.

The rapid rise of surface temperature between May 16 and 25 is the natural result of the delay in the initial warming while the necessary amount of heat is accumulated to melt the ice. A calculation indicates that the amount of heat necessary to melt the usual 0.9 m. (36 in.) sheet of ice on Waskesiu lake could raise the whole volume of lake water through 6.5° C. or more than one third the total annual range. The effect of this heat is seen to some extent in the gradual honeycombing and disintegration of the ice. Its effect is obvious in the graph from the rise of air temperature to 9.3° C. at the time of the break-up of the ice. While the ice sheet remains, the warmth of the air can be attributed

chiefly to radiation from the land since the land surface is at this time almost free of snow and quite warm. When the ice breaks it disappears very quickly and the surface water warms at a rapid rate since the sun's rays have already become intense.

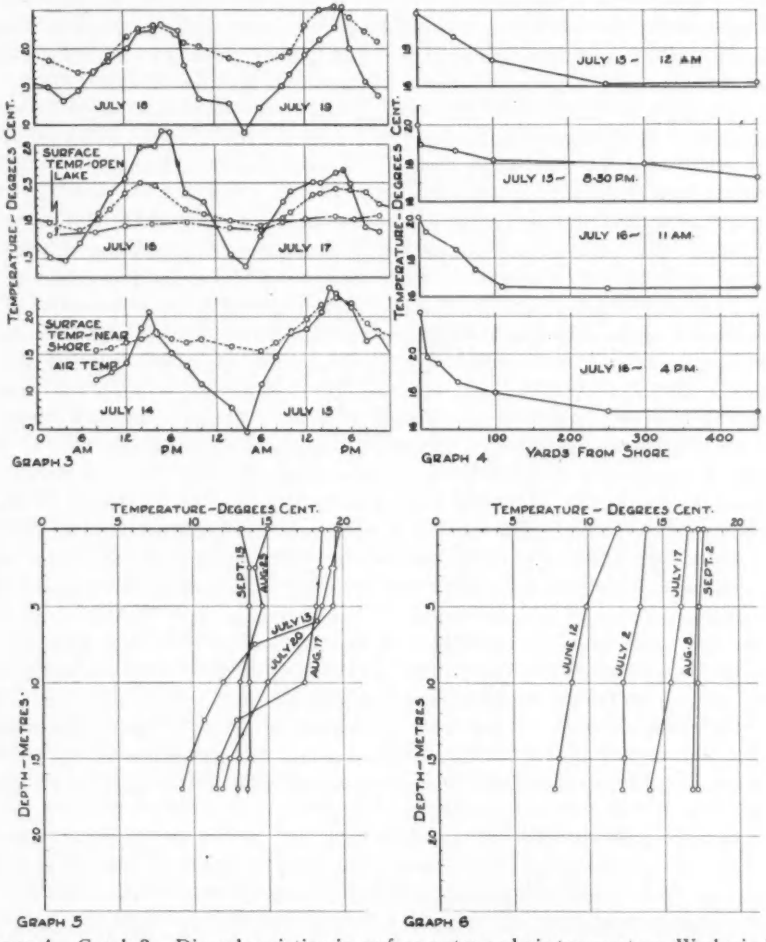
At the time of freezing another rapid change in the temperature of the surface water takes place. Since the newly formed ice is thin the amount of heat lost in its solidification is less than one per cent of that needed for the fusion of the ice in May. However the temperature must be such that an ice sheet of considerable thickness can form quickly otherwise it will be destroyed by wind action. Thus, although large sheets of ice may form as early as October 25, the final sheet is not established until November 17 when the mean air temperature has dropped to −6.0° C.

Between May 16 and 23 the temperature of the surface water remains lower than that of the lake as a whole. At the latter date the curves of surface and mean lake temperature in graph 1 are seen to intersect. From May 23 to July 25 the surface temperature continues to rise more rapidly than the mean temperature since thermal stratification is being established at this time. The cooling period begins about August 1 and from September 1 to November 17 the difference between the two temperatures is usually less than 1° C., indicating an almost complete mixture of the lake throughout this period. At about October 12 the curves intersect again and the surface temperature remains lower than the mean for the lake until freezing occurs.

In contrast with the somewhat ideal scheme represented in graph 1 discussed above, graph 2 presents similar data for a single year, 1934. In a general way it shows the irregularities in temperature change to be expected in any year, the course of air temperature being particularly irregular even though the points plotted are means of five day periods. The rough correspondence between temporary rise and fall in the surface and air temperatures suggest a degree of interdependence between these factors. It will be noted, however, that even variations of considerable magnitude in air temperature such as are to be found from August 20 to October 20 correspond to comparatively small changes in surface and mean temperature of the lake.

While the curves of air temperature in graphs 1 and 2 are of interest in relation to the water temperature curves, it is not possible to interpret this relation with any degree of completeness. The effect is complex and involves a number of factors which result in losses or gains of heat at the surface of the lake. The origin of the heat which warms the lake is obviously solar energy. Birge (1916) has indicated that of the heat delivered at the water surface during the warming period one quarter is retained by the lake. After the ice goes out the complete mixing makes possible an efficient reception of heat but the insolation is not yet strong. When, in June and July, the solar radiation becomes much more intense the lake is less able to absorb this heat because of its stratification and consequent reduced circulation. Heat losses from the surface water to the air may result from radiation by the water, evaporation and by conduction, all of which would have to be considered if air and water temperatures were to be correlated. With the available data this cannot be done. It is known,

however, that the exchange of heat between water and air by conduction is so slow as to be in most cases negligible. The rather common conception that warmer or cooler air effects changes in water temperature is therefore incorrect and the air temperature should be regarded as being controlled chiefly by radiation from water and land.



IGURE 4. Graph 3,—Diurnal variation in surface water and air temperature, Waskesiu lake. Graph 4,—Horizontal variation in surface temperature near shore at South bay, Waskesiu lake. Graph 5,—Temperature series at station I, Waskesiu lake, 1928. Graph 6,—Temperature series at station I, Waskesiu lake, 1929.

Diurnal variation in the temperature of surface water is indicated in graph 3 for the period July 14 to 19 inclusive, 1934. These temperatures were observed at South bay, and the readings taken at a point ten feet (3 m.) from the water's

edge. For comparison, air temperature for the same period is indicated and the surface temperature at station IV in the open lake is recorded for July 16 and 17.

The greatest variation in surface temperature would be expected in the shallow in-shore water. In this region the heat absorbed from the sun's rays is confined to a thin stratum and the water is not readily mixed with cooler water of the deeper layers. The reverse of these conditions is true in the open water, with the result that surface temperature is relatively stable in such locations. The daily range in surface temperature 10 feet (3 m.) from shore is indicated in graph 3 as varying from two to seven degrees during the six day period. In the open water at station IV the variations in two successive days were less than 1.5° C. The air temperature at the time was fluctuating as much as 18° C. daily and though the wind was intense on two of the days in question, no effect on the surface temperature was detected.

Horizontal variation in surface temperature has been implied in the foregoing paragraph. Two kinds of horizontal variation may be distinguished, a more or less regular decline in temperature from shore toward open water as illustrated in graph 4 and an irregular variation in different parts of the open water area. The series of temperatures plotted in graph 4 were taken in a northwest direction beginning at the bottom of South bay. By consulting figures 1 and 2 it will be seen that South bay is more than 0.8 km. (one-half a mile) wide, open broadly to the lake and is exposed to the prevailing winds. Graph 4 indicates that on July 15 and 16 the surface temperature at the water's edge was four or five degrees warmer than that of the open lake during the day. The temperature dropped rapidly for the first 91 m. (one hundred yards) and then slowly to reach the temperature of the open lake at distances of from 230 to 410 m. (250 to 450 yards). This was one factor in the decision that in this paper the term "open water" should be applied to that area not closer to shore than 0.4 km. (one-quarter of a mile) and excluding the inner parts of deep bays.

In the open water as thus limited the surface temperature was almost uniform at any one time. Variations of as much as 1.0° C. were uncommon except in a short period following the break-up of the ice. On May 15, 1932, five days after the ice broke up, the surface temperature in open water varied irregularly over a range of 2.5° C. and the average surface temperature of lower Waskesiu was 5.4°, as compared with 9.0° in the western or upper part of the lake.

VERTICAL DISTRIBUTION OF TEMPERATURE

Throughout the seven seasons vertical series of temperature determinations were made at intervals of approximately one week, at shorter intervals if conditions were known to be changing rapidly, or longer if little change was expected. These series were made at five stations on lower Waskesiu, numbered I to V on figure 1, and at one station on upper Waskesiu. In most of the years the observations extend from about the middle of May to mid-September and data for the whole year were obtained during 1934. The total number of series of temperature observations in all the years is about 280.

Since the course of temperature change was found to vary greatly in different seasons it is necessary to consider each year separately. The following accounts

are made as brief as possible by including only those data which are especially significant. For the same reason the graphs in figures 4, 5 and 6 include only those series which indicate some essential feature in the seasonal cycle of temperature. Plotting the regular weekly series of temperature observations on one graph would only obscure the meaning.

In 1928 the breaking up of the ice was complete on May 19 and was followed by a period of warm weather. In the remainder of May and early June mean air temperature was 3.5° C. above the mean for that period. Late June and early July were cool and when the first series of water temperatures was taken on July 13 the mean temperature of the lake was 15.4° C. which is 0.8° C. lower than the mean temperature at that date over the seven years of observation. As may be seen from graph 5 most of the heat gained was in the epilimnion, its mean temperature being 19.0° C. as compared with 10.3° C. the mean temperature of the hypolimnion. In other words the lake was highly stratified with a thermocline* between the depths of 6 and 8 metres. The surface water was by this time (July 13) close to its maximum temperature. Stratification persisted until August 17, the additional heat taken in by the surface water serving to increase the depth of the epilimnion and the thermocline being pushed down to a position between 10 and 15 metres. Between August 17 and 25 heavy storms resulted in a mixing of the water as may be seen from the temperature curve for August 25. Meteorological records for Prince Albert show that the winds at this period were stronger than at any other time between June 1 and September 15, the maximum being reached on August 22. From August 25 to September 15 no marked change took place, the mean temperature of the lake falling only 0.2° C. and the water becoming thoroughly mixed. The course of further cooling was not observed but ice began to form on the lake in the first week of November and the "freeze-up" took place on November 28 somewhat later than usual.

In 1929 the ice remained on Waskesiu lake until May 25. On June 12 when the first temperature series was taken the mean temperature of the lake was 9.6° C. which is about 1.5° below the average for that time. The winds in the June to August period were higher than usual and kept the lake mixed throughout the summer. As graph 6, figure 4 indicates, there was no thermal stratification during the summer, a striking contrast with conditions in 1928. At the last observation, on September 2, the lake was thoroughly mixed and at a mean temperature of 17.3° C., approximately 1.6° warmer than usual for this time. The final freeze-up occurred on November 10.

The breaking up of the ice *in 1930* occurred on May 18. Warming of the water proceeded in a regular manner and on July 4 stratification was becoming established as may be seen from graph 7, figure 5. This stratification persisted until August 22 when a mean lake temperature of 18.9° C. was observed. By September 10 the water was completely overturned and the lake had cooled

*The formal definition of a thermocline as a change of at least 1° C. per metre of depth, is adhered to in this paper for purposes of clarity. It should be noted that the distinction is quite arbitrary and that a lake which is "not quite" stratified thermally will show the ecological effects of stratification in much the same way as a lake which is "just" stratified.

rapidly to a mean of 15.3° C. On September 22 it had cooled to 13.5° C. The freeze-up was on November 20.

In 1931 the ice broke up on May 11, and on June 1 the first temperature

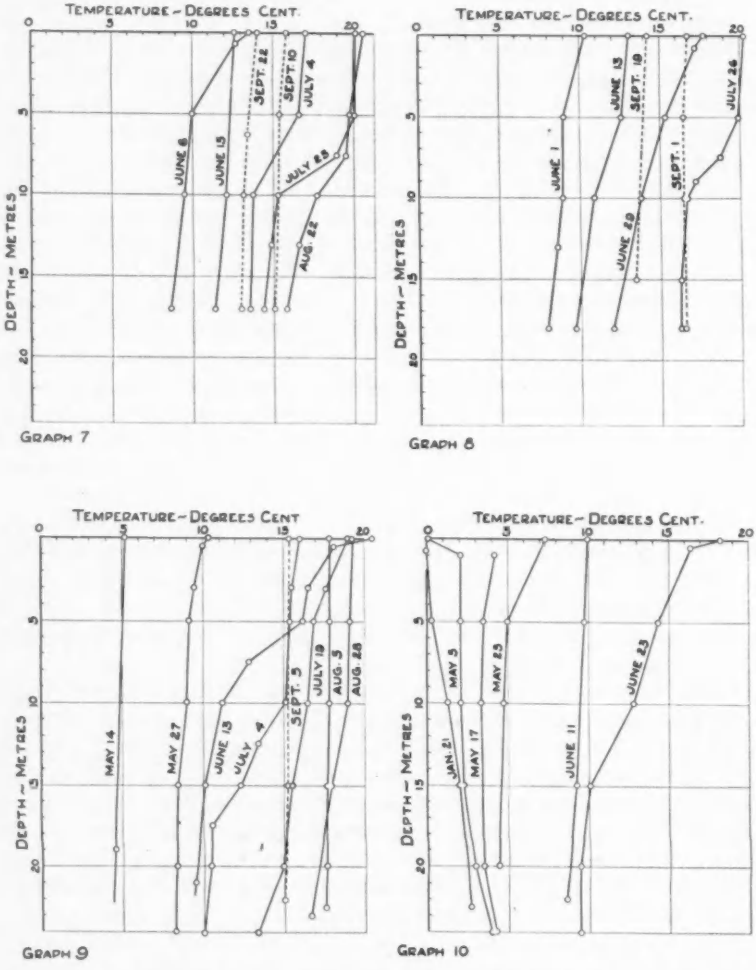


FIGURE 5. Graph 7,—Temperature series at station I, Waskesiu lake, 1930. Graph 8,—Temperature series at station II, Waskesiu lake, 1931. Graph 9,—Temperature series at station IV, Waskesiu lake, 1932. Graph 10,—Temperature series at station IV, Waskesiu lake, 1933.

observation indicated a mean temperature of 9.0° C. Warming proceeded regularly without stratification until July 26 (see graph 8, figure 5). On August 2 the stratification was still present, but by August 19 the thermocline had been

forced down to between 11 and 14 metres, while on September 1 the lake was completely overturned. This sequence of events was much like that in August 1928. Between September 1 and September 19 the mean temperature dropped from 16.5° C. to 13.7°, or 3° in 18 days, which is usual for this time of year. On November 20 the lake froze over.

In 1932 the ice broke up early, on May 10, and temperature observations were begun on May 12. From a mean temperature of 5.0° C. on May 14 rapid warming brought the lake to 9.4° on May 27. The surface temperature continued to rise rapidly until, on June 13 (graph 9, figure 5) a thermocline existed between 5 and 7 metres. On July 4 this thermocline had been forced down below the 10 metre level and on July 19 the lake was almost uniformly mixed. It remained thus for the remainder of the summer. On August 28 the mean temperature was 19.0° C., the highest observed at any time in the seven years of observation. The early destruction of the thermocline and the subsequent mixing allowed the entrance of an unusually large amount of heat into the lake water. High winds and low air temperatures at the beginning of September cooled the water, and on September 5 the lake had reached a mean temperature of 15.2° C., a decrease of 3.8° in eight days.

In 1933 observations were begun on May 5. A vertical series taken through the ice on this date appears in graph 10, figure 5. Only the bottom water, 23 to 24 metres is at 4.0° C., the temperature of maximum density. Most of the water has fallen below this point and the mean temperature of the lake is 2.1° C. On May 17 a series of observations was taken while the ice still covered three quarters of the lake surface. On this date the mean temperature was 3.6° C. The lake warmed uniformly until June 11 but on June 23 the series suggests the beginning of stratification. It was unfortunate that the season's observations had to be discontinued at this time. Ice sheets began to form on the lake as early as October 25 but the final freeze-up did not occur until November 15.

In 1934 vertical temperature series were taken throughout the year and a selection of the more significant series appears in graphs 11 and 12, figure 6. The first series, taken on January 20, indicates a mean lake temperature of only 0.68° C. It is thus evident that the lake cools to a point well below the temperature of maximum density, even the temperature of the bottom water being as low as 2.7° C. A series taken on March 8 reveals essentially the same situation, the mean temperature at that date being 0.83° C. On April 21 the mean temperature had risen to 2.06° C., a change of considerable magnitude in a lake covered by 0.9 m. (three feet) of ice. Considering the possible source of this heat we note that the snow covering the ice would exclude all solar radiation and that the amount of drainage water entering the lake is insufficient to contribute any considerable amount of heat. We therefore assume that this heat is derived by conduction from the lake bottom, which as Birge et al. (1928) have shown is considerably warmer than the water at this time. Similar conditions of warming and mixing of lake water beneath the ice have been observed by Lönnerblad (1931).

The ice broke up on May 11 and four days later, May 15, a series of temperatures showed that the lake was warming rapidly, having reached a tempera-

ture of 4.9° C. In June the upper 10 metres of water warmed much more rapidly than the lower water and on June 21 a thermocline was found between 15 and 17.5 metres. On July 3 the thermocline was found between 10 and 12.5 metres,

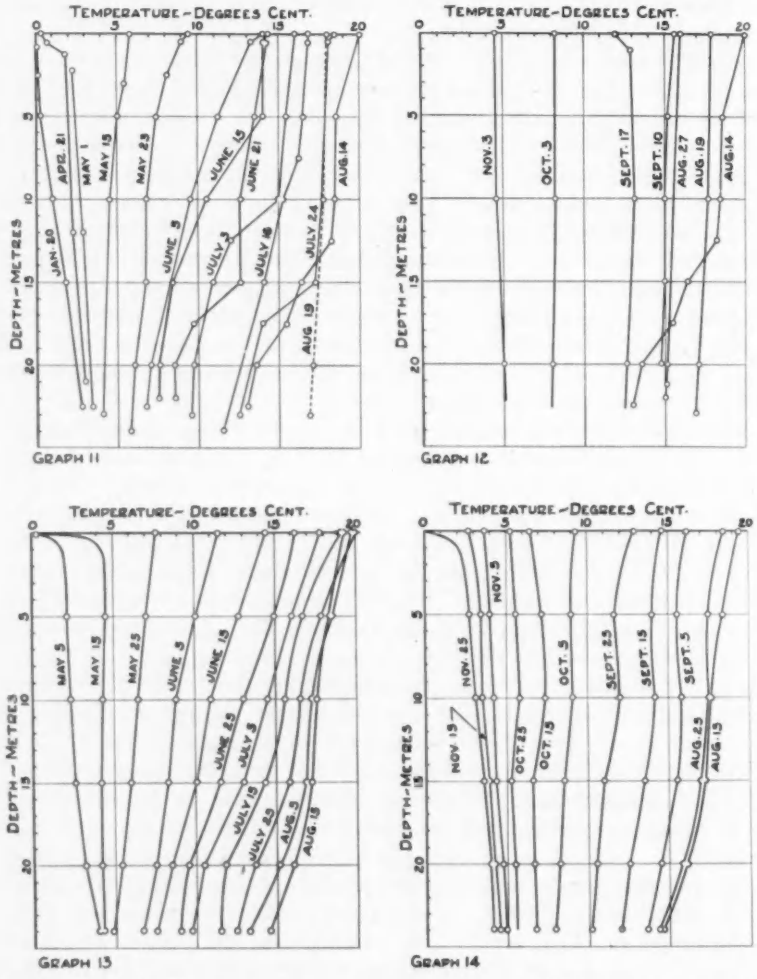


FIGURE 6. Graph 11,—Temperature series at station IV, Waskesiu lake, January to August 1934. Graph 12,—Temperature series at station IV, Waskesiu lake, August to December 1934. Graph 13,—Mean curves of vertical distribution of temperature in Waskesiu lake, May 5 to August 15 in the years 1928 to 1934. Graph 14,—Mean curves of vertical distribution of temperature in Waskesiu lake, August 15 to November 25 in the years 1928-1934.

this being the only time in seven years' observations that a thermocline was observed to rise. Between July 3 and 16 heavy winds mixed the lake so that the thermocline had disappeared on the latter date, but it was re-established on

July 24 between 15 and 17.5 metres. By August 14 only traces of stratification were left and on August 19 the lake was almost uniformly mixed at a mean temperature of 17.5° C. Although stratification occurred at various times during the summer it was never thoroughly established and even moderate winds were sufficient to disturb it.

Graph 12 shows the course of cooling from August 14 to November, 1934. Although the lake was thoroughly mixed from August 19 the rate of cooling was quite irregular. Graph 2, figure 3, indicates that wide fluctuations in the air temperature occurred in the August to October period. A sudden drop in air temperature is seen to coincide with the rapid cooling between August 19 and 27. This was followed by a rise in air temperature in the period August 27 to September 10, during which the mean lake temperature rose only 0.3° C. Between September 10 and October 3 rapid cooling resulted in a mean temperature of 5.1° C. and at the same time in graph 2 the air temperature is seen to take a low dip. Ice began to form about November 1 and the freeze-up occurred on November 21. Although ice conditions made observation of temperature impossible in December it is clear that continued cooling would be necessary to bring the lake to a mean temperature of 0.68° C., such as was observed in January, 1934.

The ideal course of seasonal temperature change in Waskesiu lake has been determined for this seven year period. All the vertical series observations were plotted in such a way that curves could be drawn to indicate the average temperature at 5, 10, 15, 20 and 24 metres at any date. From these curves temperatures were read at ten day intervals and used in plotting graphs 13 and 14, figure 6. In these graphs the special variations of any season have disappeared and the data are therefore suitable for a general discussion of seasonal temperature changes.

Graph 13, figure 6, shows the course of warming from May 5 to August 15, at which date the lake has reached its highest mean temperature, 18.2° C. The data for January to May, 1934, in graph 11 indicate a considerable amount of warming and presumably mixing under the ice, although the actual spring turnover is considered to begin with the breaking up of the ice. The end of the period of vernal circulation is not sharply marked in Waskesiu lake. On May 25 the temperature at the surface is already 3° C. warmer than at the bottom, but this difference in temperature does not produce sufficient density difference to stop circulation and the bottom temperature continues to rise steadily until June 25. Since it is agreed that with the existing temperature gradient conduction of heat to a depth of 20 metres is negligible, and since the effect of direct solar radiation scarcely penetrates beyond 10 metres (Birge and Juday 1930) it must be concluded that mixing has been in progress up to this date. It might be said therefore that while the period of complete circulation lasts for about ten days after the break-up of the ice some mixing continues for at least five weeks.

The curves for May and June indicate a rapid warming which has been calculated as 0.31° C. per day. In July and early August the rate of warming is lower, amounting to only 0.09° C. per day. Between August 5 and 15 the

mean temperature of the lake varies only 0.2° C. so this period may be regarded as the time of equal loss and gain of heat, or as Birge and Juday (1914) term it, the "equithermal period". This period as observed in lakes of Wisconsin and New York by Birge and Juday was two or three times as long as that found in Waskesiu lake.

It is noteworthy that although the lake was stratified in four of the seven years for periods of from one to five weeks, the temperature curves for July and August in graph 13 show no true stratification. Since in several of these years stratification made possible a marked shortage of oxygen in the bottom waters the situation as shown in graph 13 cannot be regarded as a true indication of the ecological conditions in the deeper water.

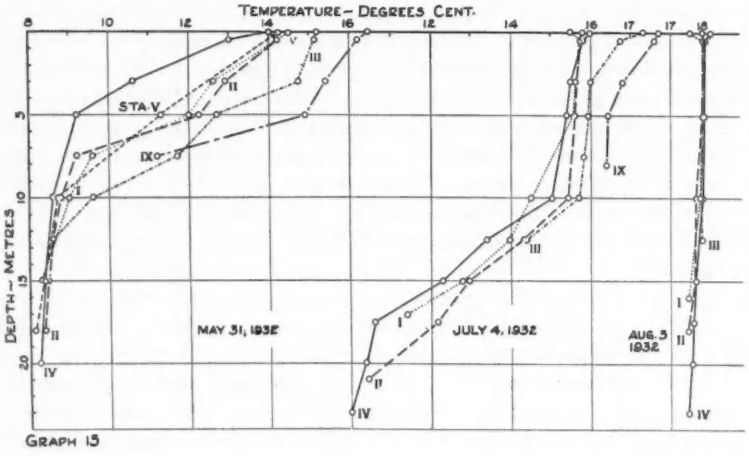
The course of cooling of the lake water is indicated in graph 14. From August 15 to September 15 cooling proceeds slowly, about 0.11° C. per day, then more rapidly, 0.2° C. per day in October and November. Stratification, if it has been established during the summer, is destroyed about the end of August. From that time the lake water is subject to continued mixture until the ice covers the lake in mid-November. Combining the vernal and autumnal periods of circulation we see that the lake waters are capable of thorough mixing for approximately three and a half of the six months when the surface of the lake is free from ice.

HORIZONTAL DISTRIBUTION OF TEMPERATURE

Simultaneous variation in surface temperature in different parts of the lake has been considered above but there remains the more fundamental question of uniformity in deep temperatures in various locations. In dealing with the quantity of heat in a lake a single vertical series of temperatures in the middle portion of the lake is often taken as representative of the whole body of water. It is recognized that this procedure is not entirely accurate and it is desirable to know the extent of the error involved. For this reason "simultaneous" temperature series were taken at five or six stations in Waskesiu lake in 1932 and 1934, and repeated at various seasons of these years, a total of nine sets of observations being taken. Truly simultaneous series could only be taken by duplicating expensive apparatus, but these series were all taken within a period of four hours and the variation in this period of temperatures other than that of the surface is probably negligible. This assumption might be incorrect if seiches occurred in the lake, but a number of attempts to detect these periodic phenomena in Waskesiu lake have been unsuccessful. Representative results from the simultaneous series have been plotted in graphs 15 and 16, figure 7.

For the interpretation of these graphs it will be helpful to examine the position of stations I, II, III, IV, V, and IX as indicated in figure 2. Stations I, II, IV and V are all within the expanded part of the lower lake. Of these, station V is in the geometric centre of the lake in the comparatively shallow depth of 15.5 metres. Station II and IV are in the two deepest parts of the lake. Station I, off Camp Two point, is at the moderate depth of 17 metres. Of the remaining stations, III is at the deepest part of the north west arm, 13.5 metres and IX at the west end of the upper lake in 9.5 metres.

Among the nine sets of observations those made on May 31, 1932, show the widest variation in temperature at the different stations. In calculating mean temperatures it is clear that because of the position of stations III and IX, series



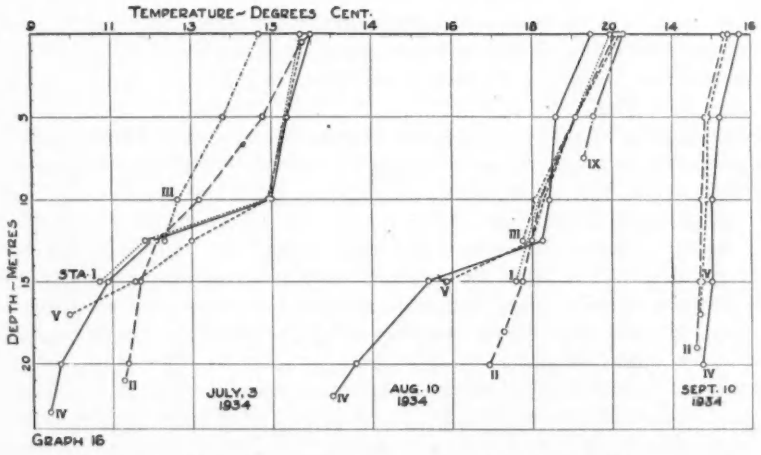


FIGURE 7. Graph 15,—Vertical temperature series taken "simultaneously" at several stations in Waskesiu lake on May 31, July 4 and August 5, 1932. Graph 16,—Vertical temperature series taken "simultaneously" at several stations in Waskesiu lake on July 3, August 10 and September 10, 1934.

from these stations should not be used as representative of the whole lake. Using series taken at stations I, II, IV and V on May 31, 1932, mean temperatures may be calculated as 10.8, 11.0, 9.8 and 10.6° C. respectively. The average of these is 10.5 and the maximum deviation, represented by the figure for station

IV, is 0.7° C. The mean temperature for the whole lake has been calculated by the laborious method of allowing each series to represent the area in which it is situated, calculating the mean temperature for each of these portions and weighting the average according to the volume of each portion. The resulting mean temperature was 10.3. If observations at station IV had been used the error would have been one of 4.9 per cent and less than this if any of the other stations were used. Similar calculations from the data for July 4, which is a more typical case, show a maximum error from using a single station of 1.6 per cent. Birge and Juday (1914) report an investigation of this problem in which they found that the use of a single series of temperatures as representative of the lakes studied produce errors of magnitude similar to those derived above. They make the logical conclusion that such errors are probably smaller than those involved in the hydrographic survey which is used in the calculation of lake temperature.

In both 1932 and 1934, the greatest variations between different stations were observed in early summer and the least variation in autumn. This tendency is illustrated by graphs 15 and 16 and supported by other series of observations in these years. It would suggest that stratification was established somewhat irregularily in different parts of the lake, that the temperature conditions became more uniform as the thermocline was forced down by the wind and that the autumnal circulation resulted in an almost uniform distribution of temperature.

In 1932 the highest temperatures were always observed at station IX, the lowest at station IV and the remainder arranged between these limits, usually in order of their position from northwest to southeast. Since it is in this direction that the depth of the lake increases, that the prevailing winds blow and that the flow from inlet to outlet of the lake occurs, it was hoped that some explanation of regional variation in temperature might be reached. In 1934, however, this arrangement was not observed, the greatest irregularity being observed on July 3 when water temperature at station III was much lower than at stations II, IV and V.

A further difference between conditions in the two years is found in the deeper water, where in 1932 temperatures at different stations are seen from graph 15 to be practically uniform, while in 1934 variations of more than 4° C. were found. Since these differences were chiefly between stations II and IV a consideration might be made of temperatures in these locations.

Stations II and IV are located in the two deepest parts and at opposite sides of the lake. The depths are 21 and 24 metres respectively. In June, 1934, the temperature of the bottom water at station II rose above that at station IV. Graph 16 shows that on July 3 the difference amounted to 1.7° C. and by August 10 to 3.5°. Significant differences in the oxygen content of bottom water were found on some but not on all of these occasions. Similar differences, but of greater magnitude, have been described by Eggleton (1931 and 1932) in a discussion of "depression individuality" in Douglas lake, Michigan. This lake is about five square miles (13 sq. km.) in area and is marked by a number of bottom depressions. In these depressions simultaneous temperatures at 22 metres depth varied as much as 11.0° C. and the dissolved oxygen also showed great

variation. In Waskesiu lake depression individuality is less marked, probably because its greater area allows more wind-caused mixing. In 1932 such individuality did not exist.

MEAN TEMPERATURE

The main changes in the temperature of the lake are shown by its mean temperature, the latter being the calculated temperature if the heat were uniformly distributed throughout the lake. Graph 17, figure 8 shows the variation of the mean temperature of Waskesiu lake throughout the year 1934 and includes also for comparison the surface and bottom temperatures.

In the first period, from January to the middle of May, the lake, though under ice, was actually warming, the mean temperature rising from 0.68° C. on January 20 to about 4.0° C. on May 11 when the ice broke up. The bottom temperature increased from 2.7° C. to 4.0° C. in the same period. In a second period, from May 11 to August 20, the surface water warmed rapidly and was roughly paralleled by the mean temperature. The bottom temperature lagged behind to the extent of about 5.0° C. indicating that the thermal stratification had been established. In the third period, from August 20 to November 3, and probably later if the data were complete, the mean, surface and bottom temperatures varied little more than 1.0° C. Thus, for a period of about three months, the lake was subject to almost complete mixture. The course of cooling after the freeze-up was not followed but it is believed that a low point in the mean temperature was reached soon after the freeze-up. It is noteworthy that in 1934 the minimum temperature was lower than 1.0° C. and that a temperature of this magnitude was maintained through the months of January and February.

Since winter data are available only for 1934 it is not possible to complete graph 1 for the remaining months. The ideal course of variation in temperature of mean, surface and bottom water as shown in graph 1 brings out some features not clearly shown in graph 17. The highest mean temperature of the lake occurs about August 10, while the surface water reaches a maximum fifteen days earlier and the bottom fifteen days later. Perhaps the most significant feature brought out by graph 17 is the extent of the vernal and autumnal circulation periods. In Waskesiu lake the period of vernal circulation is apparently very short, often less than one week after the ice has gone out. In two weeks the surface and bottom temperatures usually differ by 4.0° C. and the dissolved oxygen by fifteen per cent. These conditions differ from those found in lake Mendota (Birge and Juday 1911) where the vernal circulation lasted for more than one month. While the vernal circulation is very brief, the autumnal circulation is unusually long, lasting from two and one-half to three months. Both these conditions were quite unlike the schemes of lake temperature cycles shown by Needham and Lloyd 1916, page 34, and Thienemann 1925, page 96.

KINGSMERE LAKE

In 1928 temperature series were taken on July 31, August 28 and September 3, the curve representing the last of these appearing in graph 20, figure 9. During

this season no true thermocline occurred, although on July 31 there was a drop of 4° C. between the depths of 5 and 10 metres. It is of particular interest that

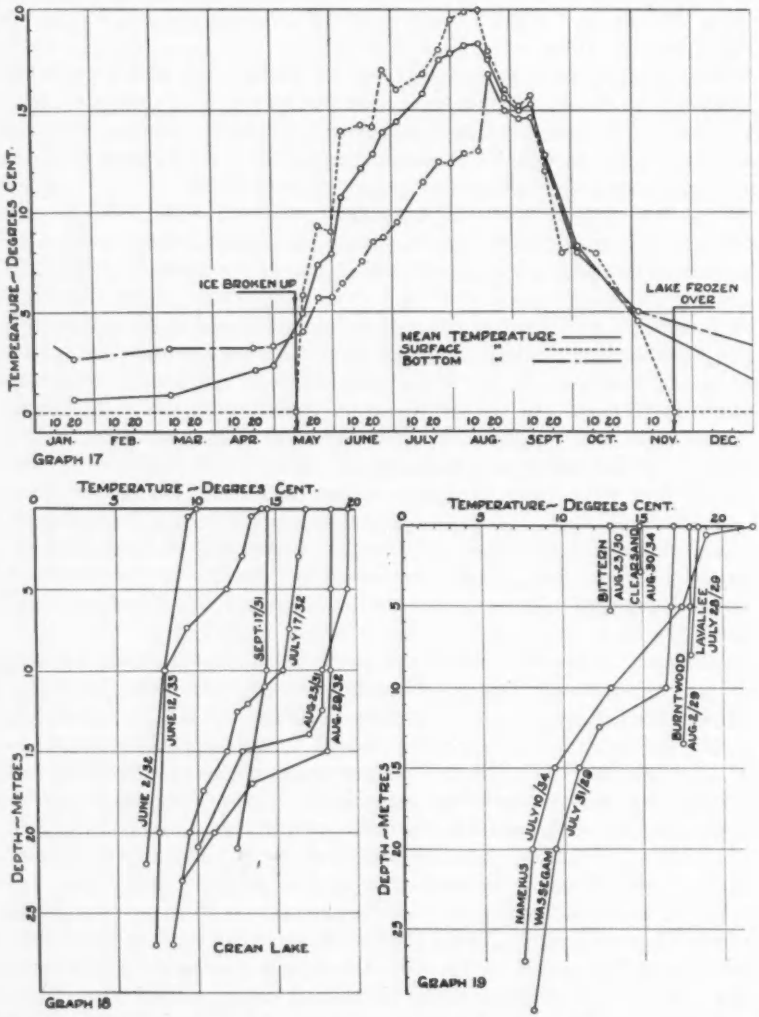


FIGURE 8. Graph 17,—Variation in the surface, bottom and mean lake temperature of Waskesiu lake during 1934. Graph 18,—Temperature series in Crean lake in 1931-32-33. Graph 19, —Temperature series in several lakes 1929 to 1934.

the storms, which in the week beginning August 17 caused a complete overturning of Waskesiu lake, resulted in Kingsmere lake merely in a change of about 2.5° C. in the temperature of the upper 10 metres of water.

In 1929, on July 19, a thermocline existed between 10 and 15 metres. On July 24, 1930, the thermocline was between 5 and 10 metres. This is the earliest date on which stratification has been observed in Kingsmere lake. As in other years the thermocline was gradually forced down throughout the summer from the relatively high position between 5 and 10 metres to a lower limit of about 17 metres.

In 1931 temperatures on June 8 were fairly uniform from surface to bottom as indicated in graph 20. At this date the mean temperature of the lake was 9.0° C. By July 16 the water in the upper 20 metres had warmed by approximately 5.0° C. but stratification had not been established. An unusual feature of this series was a sudden drop in temperature of 2.3° C. between the depths of 20 and 25 metres. On August 18 after a period of very warm weather the surface water had reached a temperature of 20° C. and a thermocline was found between 15 and 20 metres. On September 14 this thermocline had been destroyed and the temperature curve was much like that of September 3, 1928, graph 20.

In 1932 vernal circulation was apparently in progress up to May 26 when the temperature varied less than 1.0° C. from surface to bottom, as may be seen from graph 20. The mean temperature of the lake was at this time 4.8° C. On July 14 the mean temperature had risen to 9.8° C. and stratification had not yet set in. On August 26 a well marked thermocline was found between 10 and 15 metres and the mean temperature of the lake was 13.7° C. This was the highest mean observed in Kingsmere lake, as compared with 18.3° C. in Waskesiu lake on August 28 of the same year.

It may be seen from table II that about 30 per cent of the water in Kingsmere lake lies beneath the 20 metre level. This great bulk of water is naturally slow to warm or to cool, and acts as a steadying influence for temperature changes in the lake. Since the maximum bottom temperature observed was 6.9° C., it is probable that the temperature at the bottom, 45 metres, varies annually over a total range of about 5.0° C. The events of August 1928 indicate that even a severe storm had little effect deeper than 15 metres in Kingsmere lake, while Waskesiu lake, 24 metres deep, was completely mixed. The ecological effect of this mass of cold water is more clearly seen in the examination of its oxygen content and it will be discussed in that connection.

Halkett Lake

Temperature observations were made in Halkett lake during five of the seven years and the results are illustrated by a selection of five temperature series appearing in graph 21, figure 9. The temperature curves resemble those for Kingsmere lake but the level of the thermocline is more variable in Halkett lake and the stratification somewhat more severe. A greater difference is observed when the amounts of heat are considered, for the hypolimnion in Halkett lake represents only 27 per cent of its total volume, as compared with 43 per cent in Kingsmere. Although the temperature curve for August 15, 1932, is much like that for Kingsmere lake on August 26 of the same year, the mean temperatures of the two lakes are 16.1 and 13.7° C. respectively. In other words, although parts of Halkett lake are even deeper than Kingsmere, the

water of the former becomes much warmer than that of Kingsmere and almost as warm as that of Waskesiu lake.

Observations in Halkett lake indicated that, while the temperature of the hypolimnion varied as little as 0.5° C. throughout the summer, in successive years its temperature at midsummer might vary by as much as 2.7° C. The

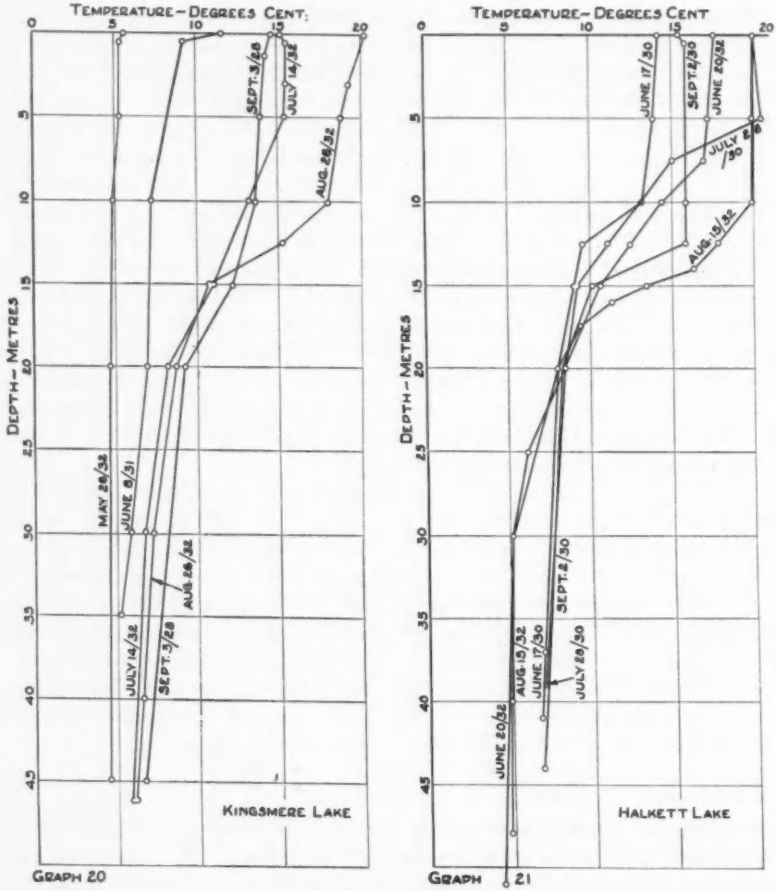


FIGURE 9. Graph 20,—Temperature series in Kingsmere lake, 1928 to 1932. Graph 21,—Temperature series in Halkett lake, 1930 and 1932.

reasonable explanation of this situation would be that it was the result of a variation of the time at which thermal stratification shuts off the circulation and downward transfer of heat. Not having exact data as to when stratification appeared in Halkett lake, the records for Waskesiu lake were examined since both lakes are exposed to the similar warming conditions. The number of days

between the break up of the ice and the first observed stratification was recorded for each year. The results show an evident correlation between the time of stratification and temperature of deep water as follows:

Year	1932	1934	1930	1931
Days from break up of ice to first stratification	33	41	47	62
Temperature 0° C. of water between 20 and 52 metres	5.0	6.0	7.3	7.7

In view of the variety of factors involved an absolute agreement would not be expected but the correlation is sufficient to confirm our supposition that in Halkett lake the temperature of the hypolimnion in different years varies according to the relative time of stratification in that year.

Crean Lake

Temperature conditions in Crean lake are illustrated by a selection of six series shown in graph 18, figure 8. In early June the lake is from one to two degrees colder than Waskesiu lake at the corresponding time. In the latter part

Table III. Gross heat budgets for four lakes in 1931 and 1932.

Lake	Area (sq.mi.)	Mean depth (m.)	Volume 10^6 (cu.m.)	1931		1932	
				Highest mean temp. (° C.)	Gross heat budget (gr.cal/cm.^{2})	Highest mean temp. (° C.)	Gross heat budget (gr.cal/cm.^{2})
Waskesiu	27	11.0	770	18.4	20,500	18.9	21,000
Kingsmere	18	21.2	990	13.0	27,300	13.7	28,800
Crean	40	11.8	1220	17.3	20,500	17.9	22,100
Halkett	3.9	10.6	107	15.0	16,200	16.1	17,100

of June a thermocline usually forms between 5 and 10 metres. The lake warms gradually and the thermocline is forced down until at the end of August it is found below the 15 metre level if storms have not upset the stratification by that time. The lake is usually overturned late in August or early in September. By mid-September the mean temperature is 13.6, cooling having proceeded to the same degree as in Waskesiu at that time.

It is noteworthy that in Crean lake the thermocline is forced as much as 5 metres deeper than in Waskesiu and that stratification persists for a considerably longer period in Crean. Waskesiu lake has an area of approximately two-thirds that of Crean. The latter has a greater depth and a considerably greater volume of water below the 15 metre level. It is suggested that the greater area of Crean lake results in more effective mixing by the wind and consequently a lower thermocline. The greater volume of the hypolimnion would resist an early overturn and the result is that the mean temperatures of Crean lake in the autumn are similar to those in Waskesiu.

A number of "simultaneous" temperature series taken at two stations in Crean lake demonstrate less irregularity of horizontal temperature distribution than has already been described for Waskesiu lake (pages 241-245).

Other Lakes of the Park

Comparative temperature data were obtained from six other lakes and a single temperature series from each appears in graph 19, figure 8.

Namekus lake has been indicated above as a small but fairly deep lake which bears some resemblance to Waskesiu. A temperature series plotted in graph 19 shows a difference of about 10° C. in the temperature of epi- and hypolimnion regions. Observations made at 5 m. intervals were not sufficient to define the position of the thermocline which was undoubtedly present at the time.

Table IV. Summary of thermal conditions in lakes of the Prince Albert Park.

Lake	Crean	Waskesiu	Kingsmere	Bittern	Lavallee	Halkett	Wassegam	Clearsand	Namekus	Tibiska
Morphometry										
Area (sq.km.)	104	70	47	31	24	10.1	9.1	8.8	7.3	7.3
Length (km.)	14	26	10	13	11	5	5	6	3.5	4
Breadth (km.)	7	5	5	3	3	3	2.5	2	2.5	2.5
Mean depth (m.)	11.8	11.1	21.2	2.3	6.5	10.6	13.5	1.6	11.9	5.5
Max. depth (m.)	27.0	24.0	47.0	5.0	14.0	32.0	25.0	2.8	27.0	13.5
Volume 10^6 (cu.m.)	1220	770	990	71	157	107	140	14	83	40
Midsummer conditions										
Highest mean lake temp. °C.	16.9	18.3	13.7	-	-	16.1	-	-	-	19.0
Bottom temp. °C.	8.4	12.5	6.0	-	-	5.5	7.8	-	7.4	18.0
Surface temp. °C.	21.0	21.0	20.0	22 ?	22 ?	20.0	21.0	22.5	21.0	21.0
Depth thermocline (m.)	10-17	6-12	10-16	none	none	11-18	10-14	none	8-12	none ?
Bottom O_2 cc/l.	1.4-4.0	0-2.3	3.8-5.2	6.0	6.2	1.1-2.5	5.0	7.0	2.5	4.6
Bottom stagnation	slight	variable	none	none	none	moderate	none	none	moderate	none
Seasonal cycle										
Duration of ice	Nov.19-May 16	Nov.17-May 16	Dec.1-May 21	Nov.12-May 13	-	Nov.12-May 13	-	-	-	-
Duration of vernal circ. (wk.)	3-6	2-4	3-6	continuous mixture	-	3-4	-	-	-	-
Duration of autumn circ. (wk.)	8	10	9		-	7	-	-	-	-
Duration of stratification (wk.)	6-9	2-8	5-7	none	none	8-10	-	none	-	none

Wassegam lake is in many respects a small relative of Kingsmere lake. The thermocline between 10, and 12.5 metres and the temperature in the hypolimnion are decidedly like those for Kingsmere lake at this season.

Lavallee lake, although fifth in area of the lakes within the park, is very shallow. On July 28, 1929, it was of practically uniform temperature, 18.0° C., from top to bottom.

Tibiska lake, into which Wassegam lake drains, is quite unlike the latter, having a mean depth of only 5.5. metres. As in Lavallee lake, the temperature on August 2, 1929, was practically uniform, 18.0° C. Bittern and Clearsand lakes are even shallower, although the former is the fourth largest of the park lakes. Because of their shallowness the temperature remains almost uniform from surface to bottom, and changes in the temperature of the lake as a whole take place very rapidly.

A partial summary of the thermal conditions in the ten lakes considered

above is presented in table IV. The seasonal temperature changes are indicated and some detail given of the conditions to be found at midsummer. In the latter connection the amounts of dissolved oxygen in the bottom water are listed as an indication of the extent of stagnation resulting from the thermal stratification. In this table the lakes are listed merely in order of area but in table V they are compared with lakes in other regions and arranged in a more logical sequence.

Heat Budgets of Lakes

Heat budgets have been used by Birge and Juday (1911) and others, as an indication of the amount of heat acquired by any lake in warming up in any summer. The annual heat budget is calculated as the number of gram calories per sq. cm. surface needed to raise all the water in the lake from its mean minimum (winter) temperature to its mean maximum (summer) temperature. Knowing the mean depth of the lake it is only necessary to multiply this in centimetres by the difference in degrees Centigrade between mean winter and summer temperature. The amount of heat which would be required to raise the lake temperature from 0° C. to the summer maximum is designated as the gross heat budget, and while the annual or net budget is admittedly more useful for comparative purposes, winter data are not always available for the calculation of the net heat received. In Waskesiu lake, in 1934, the winter minimum fell to less than one degree from the zero point, so that the difference between the two budgets is less than five per cent. It seems probable that this is the representative condition although Birge and Juday (1911) found that the lowest bottom temperature in lake Mendota varied from 1.0 to 2.5° C. in different years. The gross heat budgets in table III, for four lakes, are calculated for the years 1931 and 1932, in which years the observations were sufficiently numerous to allow a close estimate of the highest point in mean summer temperature.

It will be noted that the heat budget for each lake in 1932 is higher than for 1931 by a fairly uniform fraction and that the variations are not of great magnitude. It was found that during seven years the gross budget of Waskesiu lake averaged 20,300 gr. cal. per sq. cm., ranging from 19,200 in 1929 to 21,200 in 1933. The annual, or net, heat budget, for Waskesiu lake in 1934 was 20,500.

Kingsmere lake has a considerably greater budget than any of the other lakes and it also possesses the greatest mean depth, while Halkett lake has the lowest budget as well as the least mean depth. Birge (1916) suggested that only inland lakes of the first class, namely those which are more than 10 km. long by 2 km. wide and with mean depths of more than 30 m., could acquire the maximum amount of heat possible under weather conditions existing in the region. Since none of the lakes mentioned above have mean depths as great as 30 m., and since their heat budgets are smaller or larger according to their mean depths, it would seem probable that none of them attained the maximum heat possible in this region.

The heat budget of Kingsmere lake, which has a mean depth of 21 m., might be roughly compared with those of Keuka and Owasco of the Finger lakes (Birge and Juday 1914) which are of comparable area although their mean

depths are 30.5 and 29.3 m. respectively. Each of these lakes receives about 33 per cent more heat annually than does Kingsmere lake. In addition to their greater depth it may be noted that the mean annual air temperature at Ithaca, New York (near Finger lakes) is 8.3° C. (47° F.), while that at Prince Albert is listed as 0.0° C. (32° F.). Since the surface temperatures in both the lakes of

TABLE V. Selected data for comparison of thermal conditions

Name and location	Kingsmere Sask.	Owasco N. Y.	Green Wisc.	George N.Y.	Madusee Germany	Waskesiu Sask.	Mendota Wisc.	Trout Wisc.
Latitude	54	43	44	43	54	54	43	46
Altitude (m.)	536	217	275	98	14	530	259	492
Mean ann. air temp. (°C.)	0.0	8.5	6.7	7.7	8.0	0.0	7.8	4.0
Morphometry								
Area (sq.km.)	47	27	29.7	193	36	70	39.4	18.8
Length (km.)	10	18	12	48	15	26	9	7
Breadth (km.)	5	2	3	4	3	5	7	4
Mean depth (m.)	21.2	29.3	33.1	15	20	11.1	12.1	13.8
Maximum depth (m.)	47	54	72.2	57	42	24	25.6	35
Volume (cu.m. x 10^6)	990	780	984	2900	726	770	478	260
Midsummer conditions								
Surface temp. (°C.)	20	20	22	22	21	20	25	19.5
Bottom temp. (° C.)	6	5.3	5.3	5.5	4.9	12.5	12	6.6
Highest mean lake temp. (°C.)	13.7	13.6	11.7	-	11.7	18.3	18.5	16.0
Position of thermocline (m.)	10-17	12-20	12-18	8-15	-	6-12	7-12	8-12
Bottom oxygen (cc/l.)	4.5	5.7	4	7.1	5.1	0-2.3	0	0.3
Bottom stagnation	none	none	none	none	none	variable	severe	marked
Midwinter conditions								
Lowest mean lake temp. (°C.)	-	1.3	1.7	-	4	0.7	1.2	1.0
Minimum bottom lake temp. (°C.)	-	1.7	1.0	-	-	2.7	-12.5	1.5
Bottom oxygen (cc/l.)	-	-	7.6	-	-	1.0	0	-
Seasonal cycle								
Duration of ice cover (wk.)	24	4	18	10	7	24	14	18
Duration of vernal circulation (wk.)	3-6	-	4	-	-	2-3	4-9	4-6
Duration of autumnal circulation (wk.)	9	-	8	-	8	10	6-8	8-10
Duration of thermal stratification (wk.)	5-7	-	22	-	-	2-8	15-17	20
Ann. heat budget (gr.cal/cm.)	36000	35000	53400	-	15400	19500	20900	20700
Budget below and above 4°C. (gr.cal/cm x 10^3)	5.5+20.5	8+27	7.8+25.6	-	0+15.4	3.6+15.9	3.4+17.5	4.1+16.6

the Prince Albert park and of the Finger lakes is close to 20° C. at midsummer it is probable that the greater depth is the more important factor in the greater heat budgets of the latter.

COMPARISON WITH LAKES ELSEWHERE

To facilitate the comparison of conditions in lakes of the Prince Albert Park with those studied elsewhere, table V has been arranged with selected data

for lakes of different types and from different regions. Some of the values in table V are approximations. The policy followed was to choose from the available data from each lake values which appeared to be representative and in almost all cases the values chosen were submitted to the various authors for approval or correction. In some cases material was gathered from the work of

in lakes of the Prince Albert Park and lakes studied elsewhere.

Gr. Plöner Germany	Füresee Denmark	Nanakus Sask.	Monona Wisc.	Pinantan B.C.	Ukleisee Germany	Beasley Wisc.	Lavallee Sask.	Tibiaka Sask.	Kegonsa Wisc.	Penask B.C.
54	56	54	43	51	54	44	54	54	43	50
21	19	523	257	871	26.2	244	539	55	256	1373
8.0	7.5	0	7.8	8.3	8.0	7.5	0	0	7.8	1.0
30	9.5.	7.3	14.1	1.5	0.35	0.05	24	7.3	12.7	7.8
9	2	3.5	7	2.5	1.4	0.4	11	4	5	5
7	4	25	4	1	0.5	0.16	3	2.5	4	3
13.7	11.7	11.9	8.4	12.0	7.1	6.1	6.5	5.5	4.6	11
60.5	36	27	22.5	21	16	15.6	14	13.5	9.6	22
412	116	83	116	18	2.5	0.33	157	40	59	86
20	19.4	21	25	22	20	24	22	21	25	15
5.0	9.0	7.4	14	6.0	7.1	5.5	-	18	23	12
15.0	16.3	-	21	15	18.0	19.3	-	19	24	14
10-16	10-16	8-12	5-13	3-9	5-10	3-9	none	none	none	none
1.3	1.0	2.5	0	0	0.8	0	6.2	4.6	1.0-4.5	
severe	marked	moderate	severe	most severe	severe	most severe	none	none	none	very slight
1.6	1.7	-	1.1	-	2.7	0.7	-	-	1.0	-
2.1	1.8	-	1.2	-	3.5	2.0	-	-	1.2	-
6.0	8.5	-	3.2	-	1.9	1.2	-	-	2.0	-
-	6	-	13	18	-	13		26	13	23
-	4	-	4-5	-	-	incomplete 5-7	-	-	4-5	-
-	-	-	8-10	-	-		-	-	10-12	-
-	8-13	-	-	15	-	20	none	none	none	none
18400	17100									
3.3+15.1	2.7+14.4									

several authors and the difficulty of choice was added to by variations and conflicting data in the different sources. It should be understood that the "groups" indicated in table V are separated chiefly for convenience in comparison and are not proposed as a classification of lakes. The second and third groups for instance differ very little except in size.

Kingsmere lake is placed in the first group of five lakes which includes Owasco lake and lake George, New York (the latter studied by Juday 1921),

Green lake, Wisconsin (Birge and Juday 1911), and the Madusee in northern Germany (Thienemann 1928). These are lakes of moderate size with mean depths of 20 to 30 metres. Thermal stratification is present but its effects are not severe in these lakes, since the volume of the hypolimnion is large and bottom stagnation does not occur in summer or winter. The bottom temperature in mid-summer does not exceed 6° C. and the minimum oxygen of the bottom water is from 4 to 5 cc. per litre. Owasco is one of the smaller members of the Finger lake group in New York (Birge and Juday 1914, 1921), the larger members of the group being considered as subalpine by Halbfass 1923, Thienemann 1928, and Brehm 1930. Lakes, such as the Zurichsee Obersee and Bodensee Untersee cited by Thienemann 1928 as alpine types are quite like Kingsmere and Owasco lakes both in morphology and in thermal conditions.

In the second group, Waskesiu lake is compared with lake Mendota and Trout lake in Wisconsin (Birge and Juday 1911), the Grosser Plöner See in northern Germany and the Füresee in Denmark (Brönsted and Wesenberg-Lund 1911 and Wesenberg-Lund 1917). The areas of these lakes do not differ greatly from those of the first group but the mean depths are between 10 and 15 metres. In these lakes thermal stratification is accompanied by a more or less severe bottom stagnation in which dissolved oxygen may be absent from the bottom water for a considerable period in both summer and winter. These are typical large eutrophic lakes. A number of the north German lakes studied from the Hydrobiological Station at Plön belong to this division and some Scandinavian lakes such as the Orensee in Sweden.

Group three includes Namekus lake with Monona and Beasley lakes, Wisconsin, Pinantan lake, British Columbia (Rawson 1934) and the Ukleisee in northern Germany (Thienemann 1928). These lakes are smaller in area than those in group two but only slightly shallower. In most cases bottom stagnation is more severe. Namekus lake is almost intermediate between groups two and three. Typical examples of the small, highly stratified eutrophic lake, so numerous in Wisconsin and in northern Germany, seem to be absent or at least rare in this region.

In the fourth group Lavallee and Tibiska lakes are compared with lake Kegonsa, Wisconsin, and Penask lake, British Columbia. These are lakes of varied area in which the mean depths are only a little less than those of group three but the difference is of great consequence since circulation is complete throughout the summer. From the available data it would appear that this type is not common among lakes studied in central Europe and in Wisconsin, although a number of these were found in the Prince Albert park. It is suggested also that the maximum depth of a lake which may remain unstratified throughout the summer is considerably greater here than in regions with warmer climates.

DISSOLVED OXYGEN

The amount of dissolved oxygen in the water was investigated more thoroughly than any other chemical factor, because it was regarded as one of the most important and best understood influences in what might be called life

conditions in a lake. With each vertical series of temperature observations samples were taken for oxygen determination, at surface, bottom and at inter-

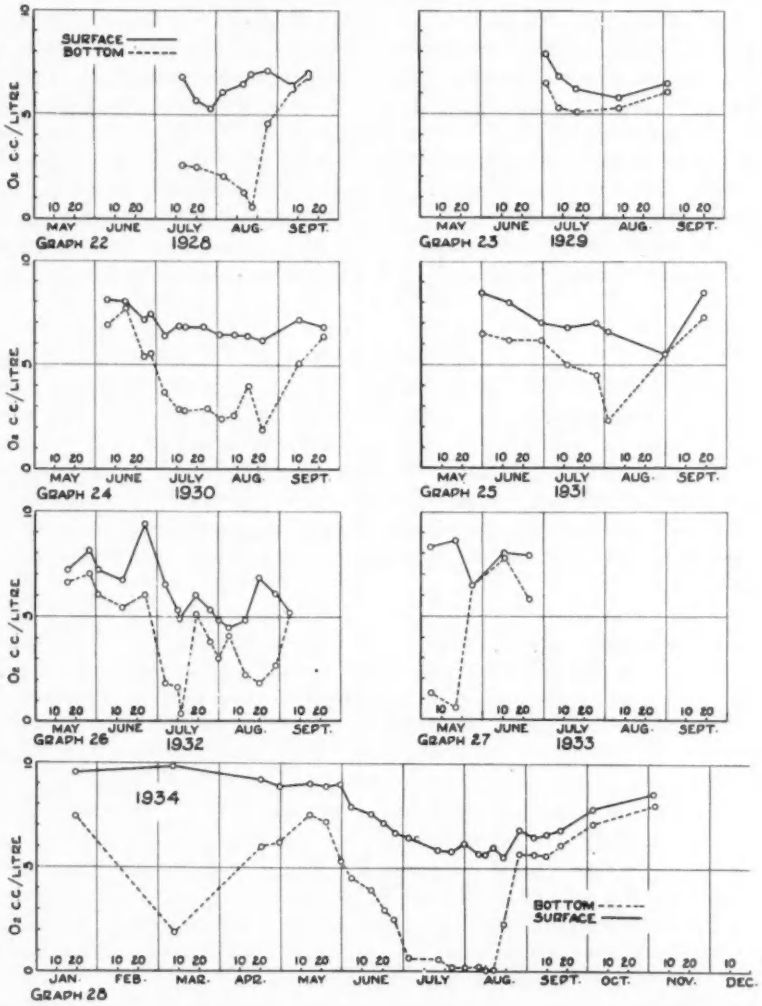


FIGURE 10. Graphs 22-27,—Variation in the amount of dissolved oxygen in surface and bottom water samples from Waskesiu lake in summers 1928 to 1933. Graph 28,—Variation in the amount of dissolved oxygen in surface and bottom water samples from Waskesiu lake in the year 1934.

mediate depths, the number of intermediate samples depending chiefly on the temperature conditions at the time. A total of about 650 oxygen determinations have been made, more than two-thirds of which were from Waskesiu lake.

Miller's method of determining dissolved oxygen, described by De Laporte 1920, has been used chiefly because of its convenience. Most of the samples were analysed at once, in the boat, and in cases where they were taken ashore they were examined immediately. In 1934 a series of tests indicated that the use of the Winkler method did not result in any significant increase in accuracy in these waters. Saturation values have been calculated from Fox's results as tabulated by Whipple and Whipple 1911, and recommended by Ricker 1934, in his critical examination of the problem. Correction for altitude has been applied, since it amounts to seven per cent of the saturation value at this level. It was not considered advisable to apply any of the varied and rather elaborate standards of oxygen saturation proposed by various workers and discussed by Ricker in the above mentioned paper. Even the altitude correction is of doubtful value until limnological investigators adopt it as a regular procedure.

WASKESIU LAKE

The amount of oxygen in surface and bottom water was determined regularly and provided a clear indication of seasonal variation, not only in the amount of oxygen but the extent of bottom stagnation. Graphs 22 to 28 show the amounts of oxygen in surface and bottom water in the summers of 1928 to 1933 and for the whole year in 1934. In table VI these data are recorded along with the corresponding saturation values. Bottom oxygen refers in all cases to the dissolved oxygen from a water sample twenty centimetres from the bottom. Data presented later will indicate the need for the arbitrary choice of sampling level.

In 1928 observations began on July 13 when thermal stratification was well established and the oxygen in surface and bottom samples 6.8 and 2.6 cc. per litre. From this time until August 17 the surface oxygen fluctuated between 5.3 and 7.1 while the bottom oxygen dropped steadily until it reached a low point of 0.6 cc. per litre. Between August 17 and 25 storms destroyed the thermal stratification as it was observed in graph 5. Graph 22 indicates that at the same time bottom oxygen was increased from 0.6 to 4.6 cc. per litre and by September 7, a uniform vertical distribution of oxygen had resulted.

In 1929 conditions in Waskesiu lake were surprisingly different from those in the previous year. Graph 6 has already shown that between June 12 and September 2 there was no indication of thermal stratification. It was to be expected therefore that the bottom oxygen would not be depleted and graph 23 shows that it was always more than 5 cc. per litre. At no time was the difference between surface and bottom oxygen more than 1.5 cc.

In 1930 thermal stratification was appearing in late June and early July. During the same period the quantities of oxygen in surface and bottom water were gradually diverging. On July 11 surface oxygen was 6.9 and bottom 2.9 cc. per litre. This condition was not greatly changed until the middle of August when temperature change indicated a mixing which raised bottom oxygen to 4.0 cc. only to have it drop to 1.9 cc. per litre on August 22, the lowest point for the season. There was thus a period of about one and one-half months in which bottom oxygen was lower than 3 cc. per litre but no period of severe stagnation.

In 1931 the bottom oxygen was not noticeably depleted in July, but on August 2 it had dropped to 2.3 cc. per litre. This is very like the situation in 1928 but we have no further data as to the course of bottom stagnation in August 1931.

In 1932 the quantities of surface and bottom oxygen were subject to sudden and large variations throughout the season. Thus after a temporary rise to 6.0 on June 24 bottom oxygen fell off to 0.3 cc. per litre on July 11. Storms at

TABLE VI. Dissolved oxygen in surface and bottom water of Waskesiu lake.

Date	Surface cc/l	% Sat.	Bottom cc/l.	% Sat.	Date	Surface cc/l.	% Sat.	Bottom cc/l.	% Sat.
1928									
July 13	6.8	113	2.6	34	Aug. 13	6.5	104	1.3	17
" 20.	5.8	95	2.5	34	Aug. 17	6.9	111	0.6	7
" 27.	5.3	81	-	-	" 25.	7.1	106	4.7	70
Aug. 3.	6.1	97	2.1	29	Sept. 7.	6.3	92	6.4	94
					Sept. 15	7.0	101	6.8	99
1929									
July 2.	7.9	116	6.5	92	Aug. 8.	5.8	92	5.3	82
" 8.	6.8	100	5.3	77	Sept. 2.	6.5	103	6.1	96
" 17.	6.2	97	5.1	75					
1930									
June 6.	8.1	117	6.9	90	Aug. 1.	6.5	109	2.4	36
" 15.	8.0	114	7.7	107	" 8.	6.5	107	2.6	40
" 24.	7.2	109	5.4	77	" 15.	6.4	114	4.0	62
" 27.	7.4	111	5.5	79	" 22.	6.2	105	1.9	30
July 4.	6.4	101	3.7	54	Sept. 10	7.2	110	5.1	77
" 11.	6.9	117	2.9	57	" 12.	7.1	107	6.2	93
" 14.	6.8	116	2.8	41	" 22.	6.8	99	6.4	92
" 25.	6.8	114	2.9	43					
1931.									
June 1.	8.5	114	6.5	83	July 26.	7.0	116	4.5	71
" 13.	8.0	114	6.2	82	Aug. 2.	6.6	110	2.3	35
" 29.	7.0	111	6.2	87	Sept. 1.	5.5	85	5.5	86
July 3.	5.6	88	5.0	77	" 19.	6.5	125	7.3	106
" 12.	6.8	106	5.0	75					
1932.									
May 16.	7.2	87	6.6	78	July 19.	6.0	97	5.1	74
" 27.	8.0	109	7.0	90	" 26.	5.3	89	3.8	59
" 31.	7.2	105	6.2	80	" 30.	4.8	78	3.0	45
June 13.	6.7	103	5.4	72	Aug. 5.	4.5	72	4.1	64
" 24.	-	-	6.0	80	" 13.	4.8	78	2.2	34
July 4.	6.5	99	1.8	25	" 20	6.8	111	1.8	29
" 10.	5.3	82	1.6	20	" 28.	6.1	101	2.6	40
" 11.	4.9	75	0.3	0.2	Sept. 5.	5.2	78	5.2	78
1933									
May 5.	8.3	88	1.3	15	June 11.	8.0	108	7.8	102
" 17.	8.6	90	0.6	0	" 22.	7.9	126	5.8	77
" 25.	6.5	82	6.5	83					
1934									
Jan. 20.	9.6	100	7.5	83	July 24.	5.8	94	0.2	2
Mar. 6.	9.9	104	1.9	21	" 31.	6.2	102	0.2	2
Apr. 21.	9.2	99	6.0	67	Aug. 7.	5.7	95	0.2	2
May 1.	8.9	94	6.2	72	" 10.	5.7	94	0.0	0
" 15.	9.0	109	7.5	87	" 14.	6.0	99	0.1	1
" 23.	8.9	118	7.2	87	" 19	5.5	88	2.3	35
" 30	9.0	113	5.3	64	" 27.	6.8	104	5.7	85
June 5.	7.9	116	4.5	66	Sept. 4.	6.5	98	5.7	85
" 15.	7.6	112	3.9	49	" 10.	6.6	101	5.6	83
" 21	7.1	105	2.9	37	" 17.	6.8	95	6.1	88
" 26.	6.7	105	2.3	31	Oct. 3.	7.8	101	7.1	91
July 3.	6.4	98	0.7	9	Nov. 3.	8.5	99	8.0	94
" 17.	6.9	94	0.6	8					

this time mixed the water so that on July 19 the bottom sample again held 5.1 cc. On August 20 it fell once more to the low point of 1.8 cc. per litre. In no other year was the bottom oxygen reduced so early in July, so it seems probable that the storms in mid-July prevented a long period of stagnation similar to that observed in 1934 (cf. graph 28).

Observations in 1933 cover the interesting period before and immediately after the breaking up of the ice. On May 17 when the ice had just begun to break up, the bottom oxygen was only 0.6 cc. per litre (see graph 32). Apparently

the effects of winter stagnation had persisted until this time. Vernal circulation in the period between May 20 and June 11 was sufficient to raise the bottom oxygen to 7.8 and to establish an almost uniform vertical distribution, surface oxygen being only 8.0 cc. per litre. The beginning of decrease in bottom oxygen is apparent on June 22, a drop of 2 cc. per litre having occurred in eleven days.

In 1934 observations were first made on January 20 and at this time the surface oxygen (under the ice) was 9.8 and at the bottom 7.5 cc. per litre. On March 8 the oxygen at the surface had not changed but at the bottom only 1.9 cc. per litre were found. Whether depletion continued is not known but on April 21 the bottom oxygen had already risen to 6.0 cc. per litre and it continued to rise until May 15. This is quite unlike the condition in 1933 when bottom stagnation persisted until the breaking up of the ice.

In May and June bottom oxygen fell off rapidly and on July 3 a stagnation condition is indicated by a bottom oxygen value of 0.7 cc. per litre. Quantities of surface and bottom oxygen did not vary greatly from this time until August 14, after which the bottom oxygen rose suddenly to 2.3 and on August 27 to 5.7 cc. per litre. This terminated the period of stagnation. From observations on October 3 and November 3 it appears that surface and bottom water maintained uniform quantities of oxygen until the freezing of the lake on November 21. Unsafe ice conditions made it impossible to obtain further data in 1934.

The wide variation in oxygen conditions in the years 1928 to 1934 precludes any general statement as to what might be considered as "usual". The amount of dissolved oxygen in the bottom water during the midsummer period varies in different years from none at all to extremes of 5.1 cc. per litre. If we consider the period from July 15 to August 15 as representing midsummer conditions, we find that for this period in the several years the average quantity of oxygen in bottom water varied from 0.24 to 5.3 cc. per litre.

	1929	1932	1931	1930	1928	1934	6 yrs.
Average O_2 in bottom water July 15 to August 15...	5.3	4.1	4.0	3.0	1.8	0.24	3.1
Minimum O_2 in bottom water July 15 to August 15.....	5.1	0.3	2.3	1.9	0.6	0.1	1.7

It is probable that the minimum values are more significant than the averages as indication of the ecological conditions in the lake. It is also evident that while in most years the oxygen relations in Waskesiu lake are eutrophic, in some years, *e.g.*, 1929, they show a distinctly oligotrophic tendency.

The vertical distribution of oxygen has been observed regularly along with the temperature series and in most cases it has been found to be closely related to the vertical distribution of temperature. This being the case, it is not neces-

sary to introduce data from all of the years of observation and only those obtained in 1934 are considered.

Table VII includes series of observations of the vertical distribution of oxygen taken throughout the year at station IV Waskesiu, and in graph 29 six of the more interesting curves are plotted. The winter data of January 20 and March 8 were obtained under difficulties and are therefore incomplete, the first full series being taken on April 21. The gradient on April 21 was fairly smooth from 9.2 at the surface to 6.0 cc. per litre at the bottom and there was no evidence of the depletion of bottom oxygen recorded on March 8. Little change

TABLE VII. Vertical distribution of oxygen at sta. IV, Waskesiu, 1934.

Date	Oxygen c.c./l. at depths of							
	0 m.	5 m.	10 m.	12.5m.	15 m.	20 m.	22 m.	24 m.*
Jan. 20	9.6	9.4	-	-	9.1	-	-	7.5
Mar. 8	9.9	-	-	8.7	-	-	-	1.9
Apr. 21	9.2	9.2	9.2	9.2	8.3	7.6	7.0	6.0
May 1	8.9	8.1	8.1	8.1	7.8	7.5	6.6	6.2
" 15	9.0	8.6	7.8	-	7.6	7.6	-	7.5
" 23	8.9	8.8	8.4	-	7.5	7.5	-	7.2
" 30	9.0	-	8.6	-	8.0	7.3	-	5.3
June 5	7.9	7.6	7.5	7.3	7.3	6.8	5.4	4.5
" 15	7.6	-	6.9	-	-	4.6	-	3.9
" 21	7.1	6.9	6.5	-	6.3	4.8	4.2	2.9
" 26	6.7	6.7	6.7	-	6.5	5.4	5.2	2.5
July 3	6.4	6.2	5.9	4.7	4.1	3.3	3.2	0.7
" 17	5.9	5.7	5.6	-	4.5	1.8	-	0.6
" 24	5.8	5.8	5.8	-	5.7	1.4	1.2	0.2
" 31	6.2	-	5.1	3.1	2.3	0.5	0.3	0.2
Aug. 7	5.7	5.7	4.5	2.3	1.5	0.5	0.5	0.2
" 10	5.7	5.4	5.3	5.4	1.3	0.4	0.3	0.0
" 14	6.0	-	5.6	5.1	3.6	0.4	0.2	0.1
" 19	5.5	-	5.1	-	5.0	4.1	3.0	2.3
" 27	6.8	6.8	6.6	-	6.3	6.1	-	5.7
Sept. 4	6.5	6.6	6.4	-	6.4	6.4	-	5.7
" 10	6.6	6.5	6.3	-	6.2	-	-	5.6
" 17	6.8	-	6.8	-	6.7	6.1	-	6.1
Oct. 3	7.8	-	-	-	-	-	-	7.1
Nov. 3	8.5	-	-	-	-	-	-	8.0

* 50 cm. from the bottom

was observed between April 21 and May 1, the curve for the latter series appearing in graph 29. After the break-up of the ice on May 11 the bottom oxygen was increased to 7.5 cc. per litre, representing a saturation of 87 per cent, but at no time was the oxygen equally distributed from surface to bottom as it was on May 25, 1933. In the remainder of May and early June thermal stratification was being established and the bottom oxygen was decreasing steadily. No marked reduction in oxygen, other than at the bottom, was observed until June 15, but on June 21, as may be seen from graph 29, the oxygen supply from

the 15 metre level downward had been considerably reduced. By comparison with graph 11, figure 6 it will be seen that this was the date at which a definable

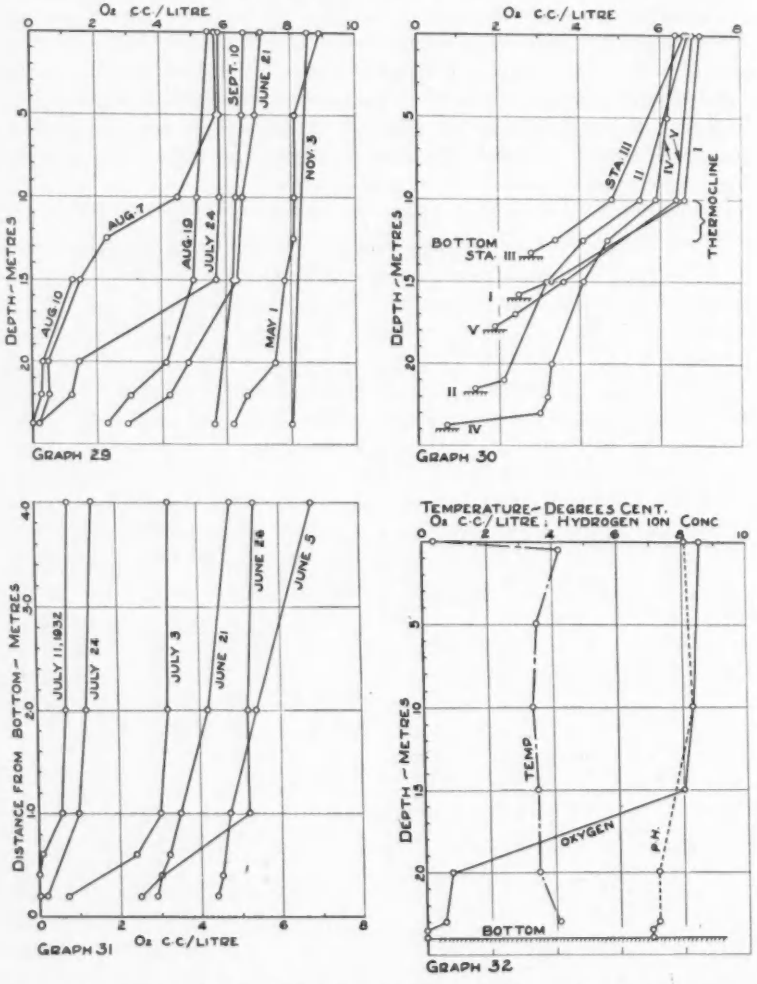


FIGURE 11. Graph 29,—Vertical distribution of oxygen at station IV, Waskesiu lake, 1934. Graph 30,—Oxygen stratification at four stations in Waskesiu lake on July 3, 1934. Graph 31,—Vertical distribution of dissolved oxygen in the lower four metres at station IV, Waskesiu lake, 1934. Graph 32,—Temperature, oxygen and pH at station IV, Waskesiu lake, May 17, 1933, when the ice was breaking up.

thermocline was observed. Oxygen decrease in the hypolimnion continued throughout the month which followed, the depleted zone increasing in its upward extent. On July 24 the bottom oxygen was nearly gone (0.2 cc. per litre)

and the average for the whole hypolimnion was only 2.1 cc. per litre. At the height of stagnation on August 7 depletion extended upward as far as the 10-metre level, and the mean oxygen content of the hypolimnion at this time reached the low point of 0.6 cc. per litre. On August 19 with the destruction of the thermocline about one half of the oxygen supply of the hypolimnion had been restored. On August 27 the bottom oxygen reached 5.7 cc. per litre and remained at approximately this level throughout the long period of autumnal mixing. On September 17 the last complete series of observations shows a simple gradient from 6.8 at the surface to 6.1 cc. per litre at the bottom.

While oxygen data for 1934 have been used in the above description it should not be inferred that these are "typical" for the lake. They show rather the extreme of summer stagnation observed in the period of seven years. In other years, when thermal stratification was less marked or absent, oxygen quantities show a proportionately smaller depletion.

The uniformity in vertical distribution of oxygen at different stations was studied along with the similar problem in temperature distribution, as discussed in pages 26 to 30. On nine different occasions in the summers of 1932 and 1934 vertical series of observations were made at stations I to V inclusive, in the course of a few hours, truly simultaneous observations being impossible. One of these series of observations, taken on July 3, 1934, appears in graph 30.

Stations I, III and V are located in more shallow regions than the remaining stations II and IV. At each of the former stations the quantity of oxygen decreases at a fairly uniform rate from 10 metres to the bottom. The decline in temperature, shown in graph 16, was also uniform from the upper limit of the thermocline at 10 metres, to the bottom. At these stations there was no definable lower limit to the thermocline and therefore no hypolimnion.

At the deeper stations II and IV, oxygen decrease in the thermocline (10 to 12.5 metres) was similar to that at the more shallow stations, but this rate of decrease was not continued beyond 12.5 metres (graph 30). A slower rate of decrease in oxygen with depth is observed between 12.5 and 15 metres, and below this level in the hypolimnion the rate of decrease is still less. The available data do not define the exact upper limit of the hypolimnion but show that it must be between 12.5 and 15 metres. At the two stations decrease in the amount of oxygen in the hypolimnion is uniform in rate but the absolute amount differs by 1 cc. per litre. At both stations observations taken in the lowest metre show a sharp decline in the amount of oxygen, presumably due to the proximity of the bottom with its oxygen demand for decomposition processes. To this second and smaller region of rapid change in the quantity of oxygen, the term microstratification or "Microschichtung" (cf. Alsterberg 1922) has been applied.

The curves in graph 30 for the shallower stations suggest that this second stratification serves to extend to an abnormal depth, the decrease due to the regular thermocline effect. For the deeper stations the hypolimnion, with a fairly uniform oxygen distribution, appears between the true thermocline and the region of microstratification. A further observation of the effect of depth on the degree of oxygen depletion is found in the fact that the oxygen content

of samples taken near bottom (20 cm.) at the five stations, varies inversely as the depth of these stations in a fairly regular manner. It is to be expected that the greatest depletion would be found at the deepest station where renewal of the oxygen supply is most difficult.

That the condition portrayed in graph 30 is typical of this time of year, or rather of this phase in thermal stratification is indicated by the fact that a series of observations taken on July 4, 1932, gave almost identical results. Later in the season when the oxygen in the lowest part of the hypolimnion becomes more nearly exhausted the gradation between shallower and deeper stations is less marked. On August 10 the oxygen in near bottom samples at station IV was 0.0 cc. and at station II 1.6 cc. per litre. These values have been referred to on page 30 with respect to "depression individuality". In the light of the foregoing paragraph, it can be assumed that such individuality in bottom depressions will occur near the end of the summer stagnation period rather than in its earlier stages.

The extent of the microstratification is shown in the curve for station IV in graph 30, where the amount of dissolved oxygen is decreased by 2.3 cc. per litre in a single metre. It is clear that under such conditions the exact level from which the bottom water sample is taken is of great importance. Two chief difficulties were encountered in the investigation of this layer. The usual deep sea reversing water bottle was inconvenient for use close to the bottom, and even with a bottle capable of use near the bottom the depth of the instrument measured from a boat on the surface even in calm water was not sufficiently accurate.

With the above difficulties in mind a special water sampler was designed with unusually large openings to allow free circulation of the water as the bottle was lowered. It was broad and short and could be closed without reversing, making it possible to take samples very close to the bottom. The difficulty of locating the exact depth of the sample was overcome by attaching a wide perforated disc to the lower end of the bottle by means of a chain, the length of which could be readily adjusted. When the disc touched the surface of the bottom the valves of the sampler were closed and measurement was thus made from the bottom rather than from the surface of the lake. This apparatus was used from 1932 to 1934 for obtaining the regular bottom water samples and for special investigation of the near bottom region.

In graph 31 the curves represent the distribution of oxygen in the lower four metres of water at station IV, Waskesiu lake, 1934. On June 5 and 25 distribution is almost regular in the lower four metres, but on June 26 a drop of 2.7 cc. per litre is observed in the lower metre. From the corresponding temperature records it is evident that the thermocline was temporarily destroyed. Circulation had increased the oxygen at a distance of one metre from the bottom, by an amount of 1.7 cc. per litre but the oxygen in the lower 40 cm. was not affected. The rapid decline in oxygen in the lower metre persisted from June 26 until the latter part of July when the depletion of "near bottom" oxygen began to extend higher into the hypolimnion. As stated above the special distribution of oxygen, as indicated in curves for June 26 and July 3, may be described as

microstratification, the equivalent of Alsterberg's "Microschichtung". It is of obvious importance both with respect to the environmental conditions in which the bottom fauna are living and the general consideration in the amount of oxygen in the hypolimnion. In the latter respect it is evident that a single "bottom water" sample taken anywhere in the lower metre may give quite misleading results. After due consideration the sample taken 20 cm. above the surface of the ooze was adopted as the bottom sample for this study.

From the work of Thienemann 1928, we infer that he found microstratification only in somewhat restricted "Tiefenkesseln", depressions to which we refer colloquially as "pot holes". In Waskesiu lake, however, this type of oxygen distribution was observed at several places including station IV which is located in a deep but also wide depression. We note also that Lundberg (1929), studying lakes in Sweden, comes to the conclusion that Thienemann has underestimated the importance of microstratification.

Winter stagnation is indicated in Waskesiu lake by oxygen samples taken beneath the ice in 1932 and 1934. The full extent of oxygen depletion is not known since the winter samples were few and difficult to obtain. In the winter of 1934 bottom oxygen decreased from 7.5 cc. per litre on January 20 to 1.9 cc. on March 8. Whether it went still lower is not known but on April 21 it had risen again to 6.3 cc. per litre and remained high until after the vernal circulation. In 1932 series of observations were made through the ice on May 5 and through the partly broken ice on May 17, both indicating a severe stagnation at the end of the winter season. On May 5 of the same year the oxygen one metre from the bottom was 1.3 cc. per litre and on May 17 at the same level, 0.6 cc. On the latter date there was no oxygen in the lower 40 cm. This distribution of oxygen is illustrated in graph 32 along with the temperature and hydrogen ion concentration. It should be noted that the ice still covered most of the lake, an open space of about one-half a mile in width allowing us to reach station IV by boat. It is also noteworthy that the temperature of the lake as a whole had risen to 3.5 and even the bottom temperatures increased slightly, while the oxygen below 20 metres showed no increase. The amount of data does not warrant any general conclusion but it appears that even in winter and under the ice, temperature and oxygen conditions may differ considerably in various years.

Various Lakes of the Park

To facilitate the comparison of oxygen content in the chief lakes under discussion, table VIII has been constructed to indicate the average quantities of oxygen of surface and bottom waters in these lakes. The minimum observed quantities of bottom oxygen are also included.

In the surface water of the various lakes the amounts of oxygen do not show any significant difference. In Kingsmere lake the mean of 7.3 cc. per litre is somewhat higher than the others, but the water temperatures are correspondingly lower so that the per cent saturation in the surface water of Kingsmere is similar to that in the other lakes.

The oxygen of the bottom water in Waskesiu lake has been discussed above

and is included here for comparative purposes. Data for six years are entered separately to call attention to the wide range of variation. Such a range of variation might suggest that observations made in different years on the remaining lakes should not be averaged, but having only 10 to 12 series from each lake this was considered the best procedure.

In Kingsmere lake the oxygen of the bottom water is higher than in any of the other lakes, the average even in the midsummer period being 4.5 cc. per litre and representing a saturation value of more than 60 per cent. The amount and distribution of oxygen is distinctly oligotrophic and in table X Kingsmere lake is used as an illustration of this condition. In Crean lake the average quantities of oxygen as indicated in table VIII are almost identical with those of Waskesiu, but the range of variability observed is much less. The minimum amount of bottom oxygen in Crean lake was lower than 2 cc. per litre on only two occasions and the lowest observation was 1.4 cc. per litre. There is there-

TABLE VIII. Dissolved oxygen in Waskesiu, Kingsmere, Crean and Halkett lakes.

	Av. Surface Oxygen cc/l May 15-Sept. 15.	Av. Bottom Oxygen cc/l May 15-Sept. 15	Av. Bottom O_2 from July 15 to autumn circul.	Minim. Bottom O_2 during summer.
Waskesiu L. 1928	6.4	3.4	1.7	0.6
" " 1929	6.6	5.6	5.2	5.1
" " 1930	6.9	4.3	2.8	1.9
" " 1931	7.0	5.2	3.6	2.3
" " 1932	6.1	4.2	2.8	0.3
" " 1934	6.7	3.1	0.24	0.0
" "1928-34	6.6	4.3	2.7	0.0
Kingsmere L. 1928-32 (12 series obs.)	7.3	6.1	4.5	3.8
Crean L. 1929-34 (12 series obs.)	6.8	4.2	3.0	1.4
Halkett L. 1929-34 (10 series obs.)	6.7	3.8	2.6	1.1

fore a much less serious deficiency of oxygen in the deeper water of Crean than in Waskesiu lake.

Halkett lake in its thermal conditions resembled Kingsmere to a considerable extent, but the dissolved oxygen indicates an important difference between the two lakes. The bottom oxygen in Halkett averages even lower than that of Waskesiu lake although the observed minimum of 1.1 in Halkett is not comparable to the absence of oxygen sometimes found in Waskesiu. Observations in Halkett lake were made at station I in 52 metres of water and since table I shows this deep area to be quite restricted, the results might not be altogether significant of the general condition. Three series of observations in parts of the lake from 15 to 25 metres deep show that the bottom oxygen in these areas is not essentially different from that at the same depths at station I.

In the seven other lakes single series of oxygen determinations have been made, the results appearing in table IX. Many of these lakes are shallow and

in them only surface and bottom samples were taken. All of these observations were taken near the midsummer period and are therefore considered to be especially significant of the oxygen conditions in the respective lakes.

Wassegam lake is more than 30 metres in depth and even at midsummer its bottom water contained 5.0 cc. of oxygen per litre. Its fauna as well as its physical conditions indicate oligotrophy.

The second lake, Namekus, is about 27 metres deep. On July 10, 1934, it was already stratified thermally and the bottom oxygen reduced to 2.5 cc. per litre. It is highly probable that a severe bottom stagnation will develop in this lake in late July and August.

Tibiska, Lavallee and Heart lakes are apparently too shallow to retain thermal stratification. The reduction in bottom oxygen in these lakes is probably the result of rapid decomposition in their rich organic bottom materials, promoted by the high temperatures which prevail. Bittern and Clearsand lakes are extremely shallow and at the time of sampling showed no difference in the amounts of oxygen present at surface and bottom.

TABLE IX. Surface and bottom oxygen in other lakes of the park.

Lake	Date	Surf. temp. (°C.)	Surf. O_2		Bott. temp. (°C.)	Bott. O_2		Depth of bottom sample (m.)
			cc/l.	% sat.		cc/l.	% sat.	
Wassegam	July 31/29	17.0	5.9	93	7.8	5.0	63	30.0
Namekus	July 1/34	22.0	6.5	113	7.4	2.5	31	27.0
Tibiska	Aug. 2/29	18.0	6.0	97	17.5	4.6	73	13.5
Lavallee	July 28/29	18.5	6.2	100	18.0	6.1	97	8.0
Heart	July 18/32	23.0	5.5	97	19.4	3.9	64	4.0
Bittern	Aug. 23/34	13.0	6.6	95	13.0	6.6	94	3.5
Clearsand	Aug. 30/34	14.8	6.7	100	14.8	6.7	100	2.5

Oxygen saturation values corrected for altitude of 530 m.

ANALYSIS OF OXYGEN CONDITIONS IN WASKESIU AND KINGSMERE LAKES

A further analysis of the oxygen conditions in these lakes has been made, using the methods of Thienemann (1928). His procedure consists essentially of the calculation of the following values, usually for the midsummer period. The total quantity of oxygen in the "epilimnion" is designated as O_2E and expressed in cc. In these designations E refers to the "hydrographic" epilimnion, that is, the 0 to 10 metre stratum. The total quantity of oxygen in the hypolimnion, indicated by O_2H, is also calculated, the hypolimnion being the remainder of the lake volume below the 10 metre mark. The ratio of the quantity of oxygen in the hypolimnion to that in the epilimnion, $O_2 H/E$ is used as an index of the degree of oligotrophy, or eutrophy in the lake. Oxygen "deficits" are also calculated, ΔE being the amount of oxygen, in cc. per litre, needed to bring the average oxygen of the epilimnion up to saturation at the existing temperature and ΔH the corresponding deficiency per litre in the hypolimnion. The deficit for the whole lake $\Delta(H+E)$ is derived from the values for ΔH and ΔE, weighting them according to the respective volumes of hypolimnion and epilimnion. Knowing

the deficit for the whole lake O_2A may be readily calculated, this being the amount of oxygen which would have to be taken in through each sq. cm. of surface in order that the deficit might be completely wiped out. The latter value is termed by Thienemann the oxygen "Aufnahme" which might be freely translated as oxygen capacity. Details of the calculation of these values are to be found in Thienemann 1928, pages 7 to 21. In order that the resulting values might be comparable Thienemann's procedure has been followed minutely although we disagree with some features of it.

The above mentioned oxygen values for Waskesiu and Kingsmere lakes appear in the central columns of table X along with a resumé of the pertinent

TABLE X. Oxygen conditions at midsummer in representative oligotrophic and eutrophic lakes. Comparative data from Thienemann (1928).

	Seneca N. Y.	Owasco N. Y.	Breiter Luzin N. Germany	Kingsmere Sask.	Madusee N. Germany	Waskesiu Sask.			Plöner N. Germany	Mendota Wisc.
Area (sq. km.)	175.	26.7	2.6	47	36	70			30	39.4
Depth max. (m.)	186	54	58.2	47	42	24			60	25.6
Depth mean (m.)	88.6	29.5	25.4	21.2	20	11.1			13.7	12.1
Vol. (cu.m. x 10^6)	15539	780	67.5	990	726	770			412	487
Vol. "E" (0-10 m.)	1640	239	23	310	303	554			231	299
Vol. "H" (10-bott.)	13900	542	44.5	680	423	216			181	178
Vol. H. ÷ Vol. E	8.5	2.3	1.9	2.2	1.4	0.39			0.78	0.59
Date	Aug. 2 1910	Aug. 13 1910	Aug. 13 20/24	Aug. 26 1924	Aug. 21 1926	Aug. 8 1929	Average midsummer 1928-1934	Aug. 7 1934	Average Aug. 1916-1921	Aug. Sep. 1906-7-8
O_2 Amounts										
O_2 E., cc/l.	7.0	6.9	6.9	6.7	6.1	5.7	6.1	5.3	7.0	4.7
Tot. O_2E, cc. x 10^{10}	1161	163	15.9	208.0	184.5	316.0	336.0	294.0	162.0	140.0
O_2H, cc/l.	6.6	7.3	7.0	5.6	3.8	5.5	2.6	1.3	3.7	0.06
Tot. O_2H, cc. x 10^{10}	18000	396	31.1	382	224.6	119	56	28	67	1
O_2H/O_2E	10.4	2.4	1.95	1.83	1.22	0.38	0.17	0.09	0.39	0.007
O_2 Deficits										
ΔE, cc/l.	-0.46	-0.42	-0.40	-0.24	0.64	0.94	0.37	1.08	-0.41	1.3
ΔH, cc/l.	0.08	0.56	1.51	2.6	2.69	1.5	4.2	5.74	4.23	7.2
Δ(H÷E), cc/l.	0.02	0.26	0.84	1.7	1.84	1.07	1.49	2.40	1.70	3.5
O_2Capacity										
O_2A, cc/sq.cm.	0.20	0.76	2.19	3.4	3.70	1.2	1.44	2.64	2.33	4.2
O_2 of bott. water										
cc/l.	8.45	6.82	5.27	4.6	5.12	5.3	1.8	0.2	1.28-3.96	0.0
% Sat.	92	80	61	54	61	79	26	2.7	15-52	0.0
Trophic nature from O_2 values	(subalpine) (oligotrophic)		Typical Olig.	Clearly Olig.	Intermediate	Clearly Eutrophic but variable			Typical Eutrophic	Strongly Eutrophic

morphometrical data. Since Waskesiu lake varies so greatly in the different years we have included not only the average values but the extremes representing on one hand no stratification, and on the other a high degree of stratification and bottom stagnation.

The quantity of oxygen per unit volume in the epilimnion and hypolimnion is not shown by Thienemann in his original tables but we have calculated it and include it here as an aid to direct comparison. This average quantity does not differ greatly in the epilimnions of Kingsmere and Waskesiu lakes in the midsummer period, Kingsmere having on August 26, 1932, 6.7 cc. of oxygen per litre compared with an average of 6.1 in Waskesiu lake. The mean temperatures of the respective epilimnions were 18.6 and 18.5° C. In the hypolimnion a very significant difference is found, Kingsmere having at this time 5.6 cc. and Waskesiu an average of 2.6 cc. per litre. It is in this region also that Waskesiu shows the wide variation from 1.3 on August 7, 1934, to 5.5 on August 8, 1929.

For O_2 H/E Kingsmere shows a value of 1.83, an evidence of its oligotrophic nature, since typical oligotrophic lakes have usually a value higher than 1.5. Values of 0.09 to 0.38 in Waskesiu indicate an eutrophic condition, any value less than 0.5 being considered typical of eutrophic lakes.

In the epilimnion, Kingsmere, like many oligotrophic lakes, has a surplus of oxygen over the saturation value amounting, in this case, to 0.24 cc. per litre and expressed as a negative deficit. In Waskesiu lake the oxygen of the epilimnion, as indicated by the average deficit of 0.4 cc. per litre, is somewhat less than the saturation value. In the hypolimnion of Kingsmere lake the deficit of 2.6 cc. per litre is above the average for oligotrophic lakes which usually range between 1.5 and 2.5. In Waskesiu the average deficit of the hypolimnion was 4.2 with a maximum of 5.7 cc. per litre. The total deficits $\Delta(H+E)$, weighting the respective deficits according to the relative volumes of H and E, are 3.6 for Kingsmere and 1.64 for Waskesiu with a maximum of 2.43 in the latter, all of these values falling within the expected range.

Comparison of Waskesiu and Kingsmere with Lakes Elsewhere

In order that the oxygen conditions in Waskesiu and Kingsmere lakes might be viewed in the proper perspective, table X includes data from Thienemann 1928 for six other lakes selected to represent a variety of trophic conditions. Seneca, Owasco and Breiter Lucin are oligotrophic types to be compared with Kingsmere; Plöner See and Mendota are eutrophic for comparison with Waskesiu and the Madüsee is one of the "intermediate" group, neither oligotrophic nor eutrophic in nature.

Seneca, one of the Finger lakes of New York (Birge and Juday 1914) is much larger than the others and also much deeper. The volume of its hypolimnion (10 m. to bottom) is 8.5 times that of its epilimnion. The quantities of oxygen in its epilimnion and hypolimnion are large and the value of O_2 H/E very high (10.4). The oxygen deficit of the epilimnion is a negative amount -0.46, indicating supersaturation to the extent of about 7 per cent. In the hypolimnion the deficit is 0.08 cc. per litre, representing an average saturation value of 99 per cent and even at the bottom saturation is still 92 per cent. Owasco is a smaller member of the Finger lakes, more readily compared with Kingsmere lake although considerably deeper than the latter. In Owasco lake the volume of the hypolimnion is 2.3 times that of the epilimnion. Oxygen values in this lake are high but more moderate than those of Seneca lake. The oxygen deficits are noticeably higher but O_2 H/E is still only 2.4 and the bottom water 80 per cent saturated. In placing Seneca and Owasco lakes at one end of a comparative series it should be noted that while highly oligotrophic they represent a somewhat special subalpine group.

Breiter Lucin is one of the north German lakes which Thienemann 1928 classes as typically oligotrophic. Although very much smaller than Kingsmere and Owasco its oxygen values are almost intermediate between the two. Its mean depth is also intermediate between those of Kingsmere and Owasco, an observation which calls attention to the much greater significance of depth than area in determining the oxygen relations of a lake.

In Kingsmere lake the oxygen conditions might be described as clearly

oligotrophic but less so than in the three lakes already considered. Its value for O_2 H/E is well within the range of 1.54-1.95 observed by Thienemann in typical oligotrophic lakes of northern Germany. In those lakes, however, the oxygen deficits are smaller than those in Kingsmere and the bottom oxygen higher. Thienemann lists the per cent saturation of bottom oxygen in his typical oligotrophic lakes as varying between 60 and 70 per cent, while Kingsmere on the date mentioned indicated 45 per cent.

The Madüsee is a second north German lake and it is placed by Thienemann in the "intermediate" group. Its inclusion here will serve to correct any impression that oligotrophic and eutrophic lakes are sharply divided. An examination of the oxygen values for the Madüsee may suggest that it has a slightly greater tendency towards oligotrophy than eutrophy but other types could be chosen to complete an intergrading series.

The wide fluctuation in the oxygen values of Waskesiu lake has been commented on above. The average of midsummer conditions in the years 1928-34 indicated in the central column are in very close agreement with the average values given by Thienemann for eutrophic lakes in north Germany. The values for August 7, 1934, representing the greatest degree of stagnation observed in Waskesiu, also fall within Thienemann's typical range. On August 8, 1929, the value of 0.38 for O_2 H/E is within the "intermediate" range but the low oxygen deficit and the high (75 per cent) saturation value for bottom oxygen are both distinctly oligotrophic. While this extreme departure from the eutrophic condition was observed in only one of the seven years, the variation during the other years was of considerable magnitude, greater, we believe, than any recorded in the better known limnological literature.

The oxygen values for Plöner See also represent the average of observations made in a number of years. Compared with Waskesiu the values indicate a somewhat greater degree of eutrophy. In lake Mendota (Birge and Juday 1911) the whole of the hypolimnion is practically devoid of oxygen and the oxygen deficits are extremely high. Such conditions would warrant the use of the term strongly eutrophic.

In the consideration of thermal conditions it was pointed out (page 258) that the small highly stratified type so common among Wisconsin and German lakes is rare in or absent from this region. Likewise, with respect to oxygen distribution we have found no small lakes with highly eutrophic characters comparable to lake Mary and others described by Juday and Birge 1932.

The methods of analysis used by Thienemann have been found most valuable in obtaining a concise view of the oxygen relations in different lakes. There are, however, certain details of his method which we have adopted in order to make the figures comparable but of which we do not approve.

The average amount of oxygen per litre in the hypolimnion has been calculated by Thienemann (1928, p. 12) by averaging all the determinations made in that region. In discussing the question of whether the separate determinations should be weighted according to the volume of the stratum which they represent, he uses data from Plöner See July 24, 1917, as an example and makes the calculations with and without volume correction. The resulting values are

8076×10^8 cc. without and 8584×10^8 cc. with the volume correction. O_2 H/E culated without volume correction is 0.58 and with correction 0.62, a difference of about 7 per cent. He points out that this is not so great when we consider other errors inherent in the sampling method. For this illustration that is quite true but in many cases the error may assume a much larger proportion, particularly when the oxygen distribution in the hypolimnion is less uniform. In an example cited below, table XI, the two methods of calculation resulted in a variation of 40 per cent in the value of O_2 H/E for Waskesiu lake. If the oxygen distribution in the epilimnion is not uniform the same type of correction should be made in it although in most cases the difference will be negligible. Even if these corrections are not applied the indiscriminate averaging of all oxygen determinations from the hypolimnion results in a smaller but significant error. It would be preferable to consider only determinations made at uniform intervals or to obtain the mean graphically from the oxygen curve.

In determining oxygen deficits, the mean temperature of the hypolimnion must be determined in order to obtain the oxygen saturation value. In deriving mean temperature Thienemann also makes use of the direct average of readings at various depths rather than correcting for volume. In the case cited below, the temperature of the epilimnion in Waskesiu lakes is 19.2 when simply averaged, 19.0 when weighted and in the hypolimnion 14.5 and 15.8°C. respectively. Using the values for mean oxygen of epilimnion and hypolimnion corrected for volume, saturation values from Whipple and Whipple 1911 and temperatures both weighted and unweighted for volume, the oxygen deficits for Waskesiu differ as follows:

	Saturation value	Mean O_2 present	Deficits
Epil. temp. unweighted = 19.2°C.	6.52	5.5	$\Delta E = 1.02$
" " weighted = 19.0	6.55	5.5	$\Delta E = 1.05$
Hypol. " unweighted = 14.5	7.18	1.9	$\Delta H = 5.28$
" " weighted = 15.8	6.99	1.9	$\Delta H = 5.09$

The results suggest that in some cases the correction of mean temperature for variation in volume of the different strata is desirable.

A further modification might be suggested in the choice of standard for oxygen solubility values. In the greater part of the work, Thienemann has used Roscoe and Lunt's table from Birge and Juday 1911. In those results which he has quoted from the work of the same authors in 1914, a revised table has been used, so that in table X, values for Seneca and Owasco lakes involving the question of saturation are not exactly comparable to those in the remainder of the table. As stated above, values for Waskesiu and Kingsmere lakes appearing in table X have been calculated with the use of the saturation standard of Birge and Juday 1911 in order to have them comparable to the figures quoted by Thienemann in the same table.

In table XI the oxygen values of Waskesiu lake, August 9, 1934, are calculated in three ways. In column "A" the values are the same as in table X and calculated according to Thienemann 1928. In "B" corrections for volume have

been made in deriving both mean temperature and mean oxygen content. The saturation values are from Whipple and Whipple 1911, recommended by Ricker (1934) in his recent discussion of the subject. In column "C" the additional correction of the oxygen saturation value for the altitude (530 m.) of Waskesiu lake has been added. The temperature observations on August 7 were as follows: 0 metres—19.9°C.; 0.5 m.—19.6; 5.0 m.—19.4; 10.0 m.—18.4; 12.5 m.—16.1; 15 m.—15.3; 20 m.—13.9; 23.5 m.—12.9. The relative volumes of the depth strata will will be found in table II.

It will be seen from table XI that the above mentioned "volume correction" has a considerable effect on the oxygen values thus calculated. Since the correction depends on the shape of the lake basin it will vary in different lakes and it should be made in order to make the results comparable. It is also clear that

TABLE XI. Oxygen values for Waskesiu lake August 7, 1934, calculated by different methods.

	"A" Calculations after Thienemann 1928. Saturation B. & J. 1911	"B" Temp. O_2 corrected for "volume" Saturation W. & W. 1911	"C" As in "B" but with correction for altitude.
Average O_2E	5.3	5.5	5.5
Total O_2E	294.0	305.0	305.0
Average O_2H	1.3	1.9	1.9
Total O_2H	28.0	41.0	41.0
$O_2\frac{H}{E}$	0.095	0.134	0.134
$\triangle E$	1.08	1.05	0.82
$\triangle H$	5.74	5.09	4.73
$\triangle (H+E)$	2.40	2.20	1.80
O_2A	2.64	2.42	1.98
Bottom O_2cc/l	0.2	0.2	0.2
Bottom O_2 % Sat.	2.74	2.69	2.88

when different tables of oxygen saturation vary among themselves by amounts which may equal the whole of the so-called oxygen deficit in cc. per litre, the selection of a saturation standard is most important.

In view of these criticisms and those of various European workers, one might well ask whether we have been justified in using Thienemann's method in the foregoing section. However, since we were not prepared to undertake a complete revision of the method, we decided that the comparative feature was more to be considered than the above objections. It is also pointed out that we have included sufficient morphometric and temperature data to allow the ready recalculation of these results on any desired basis.

In the foregoing pages oxygen has been used as an index of trophic condition. Naumann's original conception of the trophic division involved a broader viewpoint, an "allegemeine productionsbiologische Gesichtpunkt". While the oxygen conditions in Waskesiu lake vary widely from year to year it seems un-

likely that its "biological production" should do so. It is questionable, therefore, whether Waskesiu really varies from strong eutrophy to a suggestion of oligotrophy in different years or whether the case merely demonstrates the limitation of oxygen as a trophic index. In this connection we may note that Naumann (1929) considers the production of phytoplankton and the amounts of nitrogen and phosphorus in the water as the best indices of "general biological production".

CARBON DIOXIDE AND HYDROGEN ION CONCENTRATION

Information as to the carbon dioxide and acidity or alkalinity of the water is essential in a general picture of the chemical environment. In this study it provides a useful supplement to the oxygen data as indicating the degree and kind of stagnation occurring in the lake.

The free carbon dioxide was determined by titration with N/44 sodium carbonate, using phenolphthalein as an indicator. In cases where the water was alkaline to this indicator the amount of N/44 hydrochloric acid solution needed to neutralize this alkalinity was considered as indicating a negative amount of free carbon dioxide. Fixed carbon dioxide was determined by titration with N/44 hydrochloric acid and a methyl orange indicator, the procedure in both determinations being essentially that of Birge and Juday 1911, page 21. Hydrogen ion concentration was determined colorimetrically, using La Motte standards for cresol red and bromthymol blue indicators.

Free Carbon Dioxide

The amounts of free carbon dioxide in surface and bottom samples throughout the season may be observed in table XII and in graph 33. In the first observation, on April 21, the surface water taken from beneath the ice contained 1.3 cc. of free carbon dioxide per litre. After the break-up of the ice the amount of carbon-dioxide decreased, but the surface water remained acid to phenolphthalein until early June. On June 5 the surface water contained 1.5 cc. per litre, but by June 15 it had become slighly alkaline and varied from neutral to slightly alkaline to the end of the period of observation, September 4. The first analysis of a bottom water sample, on April 21, indicated the presence of 4.6 cc. free carbon dioxide. Apparently this had remained as evidence of the winter stagnation period which was indicated by the temperature and oxygen records of March 8. It is of interest that the bottom oxygen had been renewed while the free carbon dioxide was still high. In the observations on May 15, after the vernal circulation had begun, free carbon dioxide in the bottom water had dropped to 1.8 cc. per litre, representing a practically uniform distribution from surface to bottom. As the lake warmed up the free carbon dioxide of the bottom water increased somewhat irregularly with a sudden decrease at the end of June which we are unable to explain. With the onset of the stagnation period it rose rapidly to amounts of more than 9 cc. per litre, with a maximum of 11.2 on August 14, just before the autumn circulation began. The latter event resulted in the reduction and later disappearance of free carbon dioxide from the bottom water, which on September 4 was alkaline to the equivalent of 1.26 cc. of carbon dioxide per litre.

Fixed Carbon Dioxide

The fixed carbon dioxide of the surface water on April 21 was 21.8 cc. per litre, or about two-thirds of the usual amount, and the sample from 10 metres contained 32.7 cc. per litre. The situation is apparently similar to that described by Birge and Juday (1911) in lake Mendota, where a rapid inflow of drainage water had resulted in this stratum of reduced carbon dioxide content just beneath the ice. Since it is a thin layer (less than one metre in lake Mendota), its effect is not perceptible when the vernal circulation takes place. Thus in Waskesiu lake, on May 1, the fixed carbon dioxide of the surface layer was

Table XII. Seasonal data for carbon-dioxide and hydrogen ion concentration in surface and bottom water at station IV, Waskesiu, 1934. Corresponding temperature and oxygen data are included.

Date	Surface					Bottom (23.8 m.)				
	Temp. C.	O. cc/l.	CO. Free cc/l.	CO. Fixed cc/l.	p.H.	Temp. C.	O. cc/l.	CO. Free cc/l.	CO. Fixed cc/l.	p.H.
Apr.21*	0.4	9.2	1.3	21.8	8.2	3.3	6.0	4.6	31.6	7.6
May 1*	1.0	8.9	2.3	22.5	7.8	3.5	6.2	2.8	32.3	7.4
15	5.8	9.0	1.7	32.8	8.0	4.0	7.5	1.6	32.6	7.6
23	9.4	8.9	-	-	8.1	5.7	7.2	-	-	7.7
30	7.7	9.0	1.0	32.5	8.2	5.7	5.3	2.8	32.9	7.6
June 5	14.0	7.9	1.5	32.4	8.2	6.7	4.5	3.6	32.6	7.6
15	14.3	7.6	-1.3	32.6	8.2	7.5	3.9	3.0	32.6	7.4
21	14.2	7.1	-0.52	33.4	8.1	8.5	2.9	3.6	32.2	7.4
26	17.0	6.7	-0.76	32.4	8.2	8.7	2.5	1.3	32.4	7.3
July 3	16.0	6.4	-0.5	32.0	8.2	9.4	0.7	4.0	32.5	7.4
17	17.7	5.9	neut	-	8.3	11.5	0.6	5.3	-	7.4
24	18.3	5.8	neut	31.5	8.2	11.5	0.2	6.1	33.4	7.4
31	18.9	6.2	neut	32.2	8.3	12.4	0.2	10.1	34.2	7.3
Aug. 7	19.9	5.7	-0.76	32.9	8.4	12.9	0.2	9.4	34.2	7.3
10	19.5	5.7	-1.54	32.9	8.4	13.0	0.0	9.9	33.9	7.2
14	20.0	6.0	-0.56	32.9	8.3	13.0	0.1	11.2	34.6	7.4
19	17.9	5.5	-1.20	-	8.2	16.8	2.3	7.1	-	7.3
27	16.0	6.8	-1.26	33.4	8.2	15.0	5.7	0.25	32.9	8.0
Sept.4	15.2	6.5	-1.04	32.6	8.1	14.6	5.7	-1.26	33.4	8.1

* Under the ice.

22.5 cc. per litre but it has risen to 32.8 cc. by May 15. Throughout the remainder of the summer the fixed carbon dioxide of the surface varied less than 2 cc. per litre. The quantity of fixed carbon dioxide in the bottom water increased during the vernal circulation, decreased in June and then rose steadily during the stagnation period to a maximum of 34.6 cc. per litre. With the autumn circulation it decreased to an amount similar to that in the surface water. The seasonal changes in fixed carbon dioxide of Waskesiu lake agree with those described by Birge and Juday (1911) for lake Mendota in the above-mentioned depletion just under the ice, also in the decrease at all depths just after the vernal circulation and in the surface minimum at midsummer.

Hydrogen Ion Concentration

The hydrogen ion concentration (pH) was determined in each sample taken for oxygen analysis in Waskesiu and other lakes studied.

In Waskesiu lake the pH of the surface water is usually about 8.2, as may

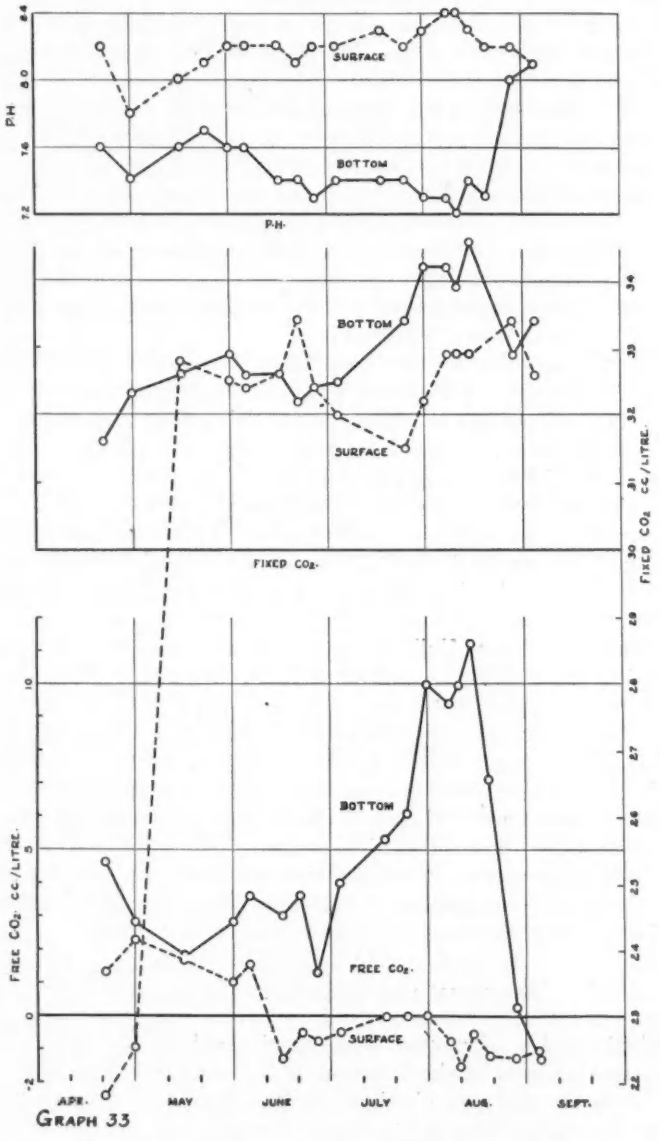


FIGURE 12. Graph 33,—Free and fixed carbon-dioxide and hydrogen ion concentration at station IV, Waskesiu lake, 1934.

be seen in table XII and in graph 32. The greatest deviation from this was a pH of 7.8 observed on May 1 when, as explained above, a thin stratum of "drainage" water was found beneath the ice. The maximum pH of the surface water was 8.4, observed on August 7 and 10. The pH of the bottom water on January 20, 1934, was 7.9, and on March 11 it had dropped to 7.5. Table XII indicates that on April 21 it was 7.6, dropping again to 7.4 on May 1. In 1933 winter stagnation conditions prevailed in the bottom water until the ice broke up and on May 17 the bottom pH was only 7.2 (graph 32). On May 23, 1934, the pH of the bottom water was 7.7, although in most years it rises to 8.0 with the vernal circulation. During the summer it dropped with some irregularity to a minimum of 7.2 in August when the free carbon dioxide content was at a maximum. At the same time traces of hydrogen sulphide were noticeable in the bottom water. Autumn circulation increased the alkalinity of the bottom water and on September 4 a uniform pH of 8.1 prevailed.

As was the case with free and fixed carbon dioxide, the variations in pH of Waskesiu lake resemble those of lake Mendota as described by Juday, Fred and Wilson (1924). Although the pH in the two lakes undergoes similar seasonal variation, the waters of lake Mendota are somewhat more alkaline than those of Waskesiu. This difference might be explained by two observations. The fixed carbon dioxide (normal carbonates) of lake Mendota vary from 35 to 40 cc. per litre as compared with 32 to 34 cc. in Waskesiu. Also the average water temperatures in lake Mendota are about 5°C. warmer than in Waskesiu lake which would result in a decreased solubility for carbon dioxide in the former and therefore a higher alkalinity.

In Kingsmere, Crean, Halkett and Wassegam lakes the pH values were essentially like those of Waskesiu lake as presented in table XII. In no case was the pH of the surface water greater than 8.7 nor that of the bottom water lower than 7.3. In some of the smaller lakes, Tibiska, Lavallee and Heart, as well as in the upper part of Waskesiu lake, thermal stratification did not persist and the pH of the bottom water was not so greatly reduced as in the deeper lakes. Even in these lakes the pH of the water was reduced to some extent, presumably by the rapid decomposition of their richly organic bottom materials promoted by relatively high temperatures. Thus in Tibiska and in Upper Waskesiu lakes, pH values of 7.5 and 7.6 were observed at times when the temperature of the bottom water varied not more than one degree from that of the surface.

MINERAL AND ORGANIC ANALYSES

A limited number of mineral and organic analyses have been obtained through the co-operation of the Department of Chemistry, University of Saskatchewan. The procedure used in these analyses was that outlined in "Standard Methods for the examination of Water and Sewage", Sixth edition, 1925.

Mineral Analyses

The results of mineral analyses of three samples from Waskesiu lake and one from Halkett lake appear in table XIII, and in the same table the average

of analyses made in Wisconsin lakes by Birge and Juday 1911. The determinations from three surface samples from Waskesiu lake can give only a general indication of the composition of its water for, as Birge and Juday and others have demonstrated, the mineral composition of water in a lake varies considerably at different depths and in different seasons. The water is distinctly hard, having a hardness indicated as calcium carbonate, of about 155 p.p.m. It contains a fairly large amount of calcium, i.e. 35 to 42 p.p.m. Such richness in calcium is regarded by Naumann (1931 and 1932), Thienemann (1925) and others as of special significance in the ecological grouping of lakes. In this connection Ohle (1934), groups lakes with more than 26 p.p.m. as rich in calcium.

The sample from Halkett lake indicates a much larger mineral content than that of Waskesiu. The chief differences are in the increased amounts of magnesium, bicarbonates and sulphates. The increased salt content may be ac-

TABLE XIII. Mineral analyses of Waskesiu and Halkett lakes with comparative data from lakes in Wisconsin. Quantities in mgm. per litre (p.p.m.).

	Waskesiu lake Surface			Halkett lake Surface	Average of 19 Wisconsin lakes*
	Jan.20 1934	Aug. 7 1934	Sep. 24 1930	Aug.31 1934	
Tot.residue evap.at 110°C.	199.0	181.0	224.0	276.1	-
Ignition loss at 950°C.	144.0	119.3	-	-	-
Total hardness as $CaCO_3$	156.6	145.1	165.5	234.0	
Alkalinity as $CaCO_3$	165.9	147.3	157.6	206.9	-
Silica (SiO_2)	5.3	10.4	5.9	3.9	11.7
Iron and Alumina (Fe_2O_3 and Al_2O_3)	2.8	1.9	0.8	2.5	2.1
Calcium (Ca)	37.2	35.0	42.1	36.8	26.9
Magnesium (Mg)	15.6	14.1	14.7	34.3	19.6
Sodium and Potassium	12.9#	15.1#	-	12.9#	5.4
Bicarbonate (HCO_3)	202.3	179.6	192.3	252.3	91.7
Sulphate (SO_4)	9.5	3.1	7.3	38.4	9.8
Chloride (Cl)	6.7	6.0	-	10.0	3.9

* Average of 74 samples at various depths in 19 lakes. Analyses made by Birge and Juday 1911.
# as Na. by difference.

counted for by the fact that Halkett lake has at present only an intermittent outlet.

The comparative data, for a group of 19 Wisconsin lakes which includes lake Mendota, is derived from 74 samples taken at various depths. The averages are those quoted in Needham and Lloyd 1916, and derived from the records of Birge and Juday 1911. It will be seen that the total mineral content of Waskesiu lake water is much higher than the average of the Wisconsin lakes. The difference is chiefly due to increased amounts of calcium and bicarbonate.

ORGANIC ANALYSIS

Eleven samples of Waskesiu lake water have been analyzed for nitrogenous materials. Of these, five were from surface, two from middle depths and four from near bottom. On two occasions samples were taken through the ice, a

third during the spring turnover and the remainder in the midsummer period. The determinations made included free ammonia, albuminoid ammonia, nitrite, nitrate and total organic nitrogen. The amounts of these materials and especially the nitrates in the different samples varied over a fairly wide range. For this reason the results are indicated below as ranging between certain limits rather than by averages.

Nitrogenous materials in eleven samples of Waskesiu lake water:

Free ammonia nitrogen	0.02 to 0.13 p.p.m.
Albuminoid ammonia nitrogen	0.20 to 0.35 p.p.m.
Nitrite nitrogen	none to 0.001 p.p.m.
Nitrate nitrogen	0.05 to 0.20 p.p.m.
Total organic nitrogen	0.50 to 1.10 p.p.m.

The water of Waskesiu lake appears to be particularly rich in nitrogenous materials as compared with that of other natural waters and in particular with that of Wisconsin lakes as reported by Birge and Juday (1926, 1927). The large amount of nitrogen is in harmony with our conception of Waskesiu as an essentially eutrophic lake.

SUMMARY AND CONCLUSIONS

The ten lakes considered vary from 7.3 to 104 sq. km. (2.8 to 40 sq. mi.) in area and have mean and minimum depths up to 21 and 52 m. respectively.

The lakes (see tables I and II) are roughly separable into four morphological groups and mean depth appears to be the most significant factor in this classification.

Temperature

The ice covers the lakes for approximately six months of the year, from mid-November to the middle of May.

In Waskesiu lake (see graphs 5 to 14) the period of complete vernal circulation is of short duration and thermal stratification is often established by July 1, although in three of the seven years no true thermocline was present. The highest mean lake temperature, approximately 18.3°C., is reached about August 10. Stratification, if present, persists for from one to two months and it is usually destroyed before August 31. The autumnal period of circulation continues for 2½ or 3 months. A minimum bottom temperature of about 2.5°C. is reached in January and the mean lake temperature this time is about 0.7°C. The water warms beneath the ice to a temperature of about 4° when the ice breaks up.

The very great difference in the thermal conditions in Waskesiu lake during seven successive years is striking evidence of how unreliable even a whole year of observations may be, in indicating the ecological nature of a lake. To this should be added the warning that *average* conditions may be almost equally unreliable, since minimum conditions are frequently critical for life in the lake.

The usual graphic representations of the seasonal cycle of thermal change do not suit the conditions in Waskesiu lake, especially with regard to the duration of the autumnal circulation.

Data for Waskesiu lake presented in graphs 15 and 16 are taken to indicate that, although temperature series taken at a single station may be used to represent temperature conditions throughout the lake without undue error, certain exceptions must be made and special care should be taken in choosing the station.

Bottom depressions in Waskesiu lake were found to contain water at different temperature and with different oxygen content, resembling, though less marked than, that observed by Eggleton in 1931 and 1934. This "depression individuality" was found to occur in some years and not in others.

The outstanding features of thermal conditions in the lakes other than Waskesiu are these (see table IV): *Kingsmere* lake has 30 per cent of its volume below the 20 metre level and its large hypolimnion acts as a stabilizing influence in temperature change. *Halkett* lake by contrast has one small deep area, the mean depth of the lake being only 10.6 m. and the temperature changes proceeding as in a shallow lake. In this lake the temperature of the hypolimnion in the midsummer period was found to vary regularly from year to year according to the length of time between the breaking up of the ice and the occurrence of stratification. *Crean* lake is like Waskesiu but with a somewhat greater body of deep water. As a result the thermocline is forced lower before stratification is destroyed and the stratified condition lasts longer than in Waskesiu. *Wassegam* resembles Kingsmere and *Namekus* resembles Waskesiu in their respective thermal conditions. The remaining lakes are sufficiently shallow that the temperature can remain almost uniform from surface to bottom during the summer.

The gross heat budget of Waskesiu lake averages 20,300 gr. cal./cm.^{2} and the net or annual heat budget is about 19,500 gr. cal./cm.^{2} Kingsmere lake, with a mean depth of 21.2 m., approaches most nearly the minimum depth of 30 metres suggested by Birge (1916) for lakes of the first class. This fact and the difference in latitude are considered an explanation for the lower heat budget of Waskesiu as compared with the smaller Finger lakes of New York.

Kingsmere is compared (table V) with a group of deep, stratified lakes with a large hypolimnion, low bottom temperature and an abundance of oxygen in the deep water. These lakes are mostly oligotrophic and some of them tend towards the subalpine type. Waskesiu is shown with a group of large eutrophic lakes in which thermal stratification is accompanied by a more or less severe bottom stagnation. The oxygen of the bottom water is very low or lacking in midsummer and midwinter. Namekus is placed with a group of small eutrophic lakes, although it is almost intermediate between this group and the large group represented by Waskesiu. In small eutrophic lakes the shallowness is related to higher temperature and still greater bottom stagnation. Lavallee and Tibiska lakes are indicated as representatives of a varied group of lakes in which circulation is complete throughout the summer. It is suggested that this condition is more frequent in lakes of this region than among other lakes studied and that lakes which remain mixed here may be of somewhat greater depth than such in warmer regions.

The mean depth is concluded to be the most significant single factor in determining the thermal nature of a lake. If thermal stratification is present, the relative volume of the hypolimnion may be a still better index. The area of a

lake is of some importance but lakes may vary greatly in area and be quite similar in their thermal conditions.

OXYGEN

The amounts of oxygen in Waskesiu lake and the general course of its variation was followed by the analyses of surface and bottom water samples in the summers of 1928-33 and through the whole year 1934. The results are indicated in table VI and in graphs 22 to 28. In the summers of 1928, '30 and '34, the bottom oxygen was rather severely depleted for a considerable period of thermal stratification. In 1931 and '32 stratification was irregular and the bottom oxygen varied accordingly, with no extended periods of depletion. In 1929 there was no thermal stratification and the bottom oxygen was only slightly lower than that of the surface. In the various years the average amount of oxygen present in the bottom water during the midsummer period, July 15 to August 15, varied from 0.24 cc. in 1934 to 5.3 cc. per litre in 1929.

Examining the vertical distribution of oxygen, significant differences were found between stations of various depths. At shallower stations the oxygen decline of the thermocline region sometimes continued beyond the normal lower limit of this layer, apparently as a result of oxygen consumption at the bottom.

Special equipment was devised to investigate the oxygen content near the bottom and a well-defined microstratification of oxygen was demonstrated. In 1934 this condition was observed in late June and early August when the oxygen curve showed a sudden decline in the lowest metre, of 2.5 cc. per litre, a drop greater than that in the thermocline (see graphs 30 and 31).

Winter stagnation was demonstrated under the ice in May, 1932, and March, 1934. The depletion of oxygen in the deep water was severe in both cases but the duration of the stagnation period was not determined.

The quantities of oxygen in Kingsmere lake are greater than in any of the other lakes of the park. Crean lake resembles Waskesiu but has more oxygen in its deeper water, and Halkett lake, although very deep in one region, has more oxygen than Waskesiu. Among the other lakes Wassegam was found to be like Kingsmere, Namekus like Waskesiu and the remaining lakes mostly shallow and high in oxygen since they remain unstratified thermally.

Quantities of oxygen in Waskesiu and Kingsmere lakes have been compared with each other and with a series of oligotrophic and eutrophic lakes, using Thienemann's (1928) method of analysis. These calculations provide index values for the relation of the amounts of oxygen in the hypolimnion to that of the epilimnion and the "oxygen deficits" or amounts needed to bring the oxygen up to saturation value. Using these and other values it is possible to designate Kingsmere as a lake clearly oligotrophic with respect to oxygen and not unlike such oligotrophic lakes as Breiter Lucin in northern Germany. It is less extreme in its oligotrophy than Owasco and Cayuga of the Finger lakes of New York. Similarly Waskesiu is described as clearly eutrophic but more variable than most eutrophic lakes on record. Its average values are roughly comparable to those of the Plöner See in North Germany and it is much less severely eutrophic than lake Mendota, Wisconsin. Data for the Madüsee, also in north Germany, show a

condition intermediate between the oligotrophic and eutrophic types. It is included to call attention to the intergrading of the two primary conditions.

Suggestions have been made for the minor changes in the application of Thienemann's indices, notably the correction of mean oxygen and mean temperature values for variation in volume of the depth strata and the adoption of the oxygen solubility standards of Whipple and Whipple 1911.

Although the oxygen conditions in Waskesiu lake vary widely from year to year it is doubtful whether this indicates as great a change in the trophic condition. The situation suggests the limitations of oxygen as a single index of trophic condition.

Additional Chemical Data

The free and fixed carbon dioxide and the hydrogen ion concentration show the expected relation in the course of seasonal variation (graph 33). In April a layer of "drainage" water, low in fixed carbon dioxide, was found just beneath the ice. As stratification progressed the amount of free carbon dioxide in the lower water increased to a maximum of more than 10 p.p.m. in mid-August. Autumn circulation restored uniformity in the distribution of both free and fixed carbon dioxide.

Mineral analyses show that the water of Waskesiu lake is fairly hard and rich in calcium. Nitrogenous materials were found in comparatively large quantities for natural waters.

REFERENCES

Alsterberg, G. *Lunds Univ. Årsskr.* N.F. Avd. 2, **18**, 1922.

American Public Health Association. Standard methods for the examination of water and sewage. 6th Ed., 1925.

Birge, E. A. *Trans. Wis. Acad. Sci.* **18**, 1916.

Birge, E. A. and C. Juday. *Bull. Wis. Geol. Nat. Hist. Surv.* **22**, 1911.
Bull. U.S. Bur. Fish. **32**, 1914.
Bull. Wis. Geol. Nat. Hist. Surv. **27**, 1914.
Bull. U.S. Bur. Fish. **37**, 1921.
Bull. U.S. Bur. Fish. **42**, 1926.
Proc. Amer. Phil. Soc. **66**, 1927.
Trans. Wis. Acad. Sci. **25**, 1930.

Birge, E. A., C. Juday, and H. W. March. *Trans. Wis. Acad. Sci.* **23**, 1928.

Brehm, V. Einführung in die Limnologie. Berlin, 1930.

Brönsted, J. N. and C. Wesenberg-Lund. *Int. Rev. Hydrob. Hydrog.* **4**, 1911.

De Laporte, A. V. *Bull. Prov. Bd. Health Ont.* Rev. **7**, 1920.

Eggleton, F. E. *Ecol. Monog.* **1**, 1931.

Halbfass, W. Grundzüge einer vergleichenden Seenkunde. Berlin, 1923.

Juday, C. and E. A. Birge. *Trans. Wis. Acad. Sci.* **27**, 1932.

Juday, C. et al. *Rep. N.Y. State Cons. Comm.* Albany, 1922.

Juday, C., E. B. Fred and F. C. Wilson. *Trans. Amer. Micros. Soc.* **43** (4), 1924.

Lönnerblad, G. *Lunds. Univ. Årsskr.* N. F. **27**, (14) 1931.

Lundberg, F. Über die Sauerstoffschichtung der Seen im Sommer. *Botaniska Notiser* **1929**, 1929.

Naumann, E. *Lunds Univ. Årsskr.* N. F. **2** (17) 1921.
Arch. Hydrob. **22**, 1929.
Grundzüge der regionalen Limnologie. Die Binnengewässer XI, Stuttgart 1932.

NEEDHAM, J. G. AND J. T. LLOYD. The life of inland waters. Ithaca, New York, 1916.
OHLE, W. *Arch. Hydrob.* **26**, 1934.
RAWSON, D. S. *Bull. Biol. Bd. Can.* **42**, 1934.
RICKER, W. E. *Ecology.* **15**, 1934.
THIENEMANN, A. *Arch. Hydrob.* **13**, 1922.
Verh. Zool-Bot. Ges. **77**, 1927.
Die Binnengewässer Mitteleuropas. Die Binnengewässer I Stuttgart, 1925.
Der Sauerstoff in eutrophen und oligotrophen Seen. Die Binnengewässer IV. Stuttgart, 1928.
WESENBERG-LUND, C. *Vidensk. Selsk. Skr. Nat. Math.* **8**, 1917.
WHIPPLE, G. C. AND M. C. WHIPPLE. *J. Amer. Chem. Soc.* **33**, 1911.

Calculations in the Investigation of Oils and Fats with Special Reference to Fish Oils. Part II.

By F. Charnley
Pacific Fisheries Experimental Station

(*Received for publication December 18, 1935*)

ABSTRACT

The equations given in Part I showing the relationships between the iodine value and saponification equivalent of mixtures of fatty acids or their esters and those of the individual components have been expressed in a simplified notation. Equations for the following fundamental relationships have also been derived: (*a*) the relation between the weight and saponification equivalent of a mixture of hydrogenated esters and the weight and saponification equivalent of the original mixture; (*b*) the relation between the weight and iodine value of a mixture of esters and the weight and iodine value of the original esters. Equations involving thiocyanogen values have been introduced. In the case of simple mixtures these equations afford a means of testing the truth of the assumptions underlying the thiocyanogen method of analysis. Also, an illustration of the method of dealing with analyses involving redundant data has been given.

The equations which were derived in part I of this series (Charnley 1934a) may, as shown there, be readily applied in estimating the composition of an oil or fat. With certain modifications and extensions to be described in the following communication, they can also be employed usefully in the study of other problems pertaining to oils and fats. Introducing the thiocyanogen value, for example, should make available a more rapid, although as yet possibly a somewhat approximate, method of following the changes in composition of the more complex marine oils during hydrogenation. In addition, the equations enable certain constants such as the percentage of saturated esters (or acids) and the saponification equivalent to be more effectively employed in the analysis of fats and oils. Finally the equations afford in some instances alternative methods of deducing certain relationships, which in part I were regarded as definitions or were arrived at on purely stoichiometric grounds.

NOTATION

In order to simplify and condense the material treated in this paper it will be found convenient to adopt a notation analogous to that employed in dealing with tensors (Thomas 1931), when referring to mixtures of fatty acids or their esters. Equation (7), part I, for example, namely,

$$\frac{I_t}{25400} = \frac{p_1}{b_1} + \frac{p_2}{b_2} + \ldots + 2\left(\frac{q_1}{c_1} + \frac{q_2}{c_2} + \ldots\right) + 3\left(\frac{r_1}{d_1} + \frac{r_2}{d_2} + \ldots\right) + \ldots$$

$$\Sigma p + \Sigma q + \Sigma r + \ldots = 1 - s$$

J. Biol. Bd. Can. 2 (3) 1936.

may be written

$$(34)\ldots\ldots \qquad \frac{I_t}{25400} = \frac{jp_{jk}}{b_{jk}}$$

where $p_{jk}=1-s$, if it is understood that the term in the right member is to be summed over the values of the indices, $j=1, 2, \ldots n$; $k=1, 2, \ldots m_1, \ldots, 1, 2, \ldots m_j$. Equation (3), part I, then becomes

$$\frac{I_u}{25400} = \frac{jp_{jk}}{b_{jk}} \qquad (p_{jk}=1),$$

while equation (13), part I, in the abbreviated notation is

$$(35)\ldots\ldots \qquad \frac{1}{E_t} = \frac{p_{jk}}{b_{jk}} \qquad (j=0, 1, \ldots n).$$

Similarly various other equations mentioned in part I may be expressed in this simplified and compact form.

THE DERIVATION OF CERTAIN FUNDAMENTAL RELATIONSHIPS

(*a*) The calculation of the weight of a mixture of hydrogenated esters from the saponification equivalent and the original weight of the esters.

Weight proportions (or molecular proportions as defined in part I) are evidently not exactly comparable when the mixture of esters under consideration has been hydrogenated to a higher state of saturation; for then 1 gram of the original mixture corresponds to a slightly greater weight of hydrogenated esters. To make these proportions comparable they must be multiplied by the weight of the hydrogenated esters corresponding to 1 gram of the original esters.

This latter quantity, however, is easily obtained from a knowledge of the saponification equivalents of the original and of the hydrogenated esters. Since on hydrogenation, V_t, the saponification value, varies inversely as w, the weight of hydrogenated esters corresponding to 1 gram of the original mixture, E_t varies directly as w, that is,

$$E_t = kw.$$

A more formal, though perhaps unnecessarily elaborate, derivation readily follows from the fact that

$$d\left(\frac{w}{E_t}\right)=0,$$

since the total number of gram molecules of esters remains constant; and therefore

$$\frac{E_t \dfrac{dw}{dI_t} - w \dfrac{dE_t}{dI_t}}{E_t^2} \cdot dI_t = 0.$$

Hence

$$E_t \cdot \frac{dw}{dI_t} = w \frac{dE_t}{dI_t} \text{ or } \frac{E_t}{w} = \frac{dE_t}{dw}.$$

On integration this equation gives the formula already shown.

If E_t' is the equivalent of the original mixture of esters and the weight taken is 1 gram ($w=1$), then $K=E_t'$, and the required equation

(36)..... $$E_t=E_t'w$$

gives w in terms of the equivalents.

(*b*) The relation between the weight of the hydrogenated esters and the iodine value.

This relationship is not, as perhaps might be expected at first sight, a simple proportional relationship. By the definition of iodine value it follows that w' grams of esters of iodine value I_t', yield on hydrogenation $w'+\frac{2I_t'.w'}{25400}$ grams of fully saturated esters, that is,

$$w_s=w'\left(1+\frac{2I_t'}{25400}\right) \qquad (H=1),$$

where w_s is the weight of the fully saturated esters. Also if w is the weight of esters obtained by hydrogenating w' grams of original esters down to an iodine value of I_t, then

$$w_s=w\left(1+\frac{2I_t}{25400}\right)$$

$$=w'\left(1+\frac{2I_t'}{25400}\right).$$

From these equations

$$w=w'\left(\frac{12700+I_t'}{12700+I_t}\right),$$

which reduces to

(37)..... $$w=\frac{12700+I_t'}{12700+I_t},$$

when the basis of w is 1 gram of original esters ($w'=1$).

For most practical purposes it will be found better to use equation (37) rather than the alternative relation given in (36), since it will in general furnish somewhat more accurate values of w than those calculated from the equivalent. Furthermore equation (37) readily enables the interval of iodine value corresponding to a given error in w to be calculated. If, for example, Δw denotes the allowable error in w, that is, the allowable error in the weight proportions or molecular proportions over a given interval of iodine value, then equation (37) shows that

$$w-1=\frac{12700+I_t'}{12700+I_t}-1=\Delta w,$$

which by simple transposition of the terms reduces to

$$\frac{I_t'-12700\Delta w}{1+\Delta w}=I_t.$$

Thus the lower limit of the first interval for a sample of pilchard oil of iodine value 180 (I'_t) and an allowable error in w of 0.005 (Δw) is 115.9. Hence in the interval of iodine value 180 to 115.9 it is in this instance not necessary to apply corrections to weight or molecular proportions for changes in weight of the esters resulting from hydrogenation. Succeeding intervals will, of course, be approximately of the same magnitude.

Finally, by substituting the value of w as given by (37) in equation (36) there results equation (38), from which the equivalents of the mixture of esters corresponding to given iodine values can be calculated.

$$(38)\ldots\ldots \qquad E_t = \frac{K}{12700+I_t}.$$

Here $K = E_t'.(12700+I_t') = 12700E_s$, since when $I_t' = 0$, $E_t' = E_s$. The truth of this statement is also readily forthcoming from the equation corresponding to (18), part I, for

$$\begin{aligned} E_t'(12700+I_t') &= 12700\,E_t' + I_t'E_t' \\ &= 12700E_t' + 12700\times 2a_t' \\ &= 12700E_s, \end{aligned}$$

where E_s is the equivalent of the mixture when it has been completely transformed into saturated esters and a_t' is the average unsaturation of the original esters.

The application of this equation may be illustrated by calculating the equivalent of the sample of pilchard oil studied by Brocklesby and Charnley (1933) when the iodine value had been reduced by hydrogenation to 50. In this case $E_t' = 274.7 + 12.7 = 287.4$ and $I_t' = 180.0$, whence $K = 370.17\text{x}10^4$. Therefore

$$E_t = \frac{370.17\times 10^4}{12700 + 50} = 290.3.$$

(*c*) Alternative forms of equations (34) and (35) in which the denominators b_{jk} are expressed in terms of N, the number of carbon atoms in the lowest member of the series in the mixture and the indices j and k.

To write down these alternative equations it is only necessary to note that, when the components of the mixture consist of fatty acids, any specified molecular weight b_{lm} ($j=l$, $k=m$) is given by the equation

$$\begin{aligned} b_{lm} &= 14(N+2m-2)-2l+32 \\ &= 14\,(N+2m)-2l+4. \end{aligned}$$

If the components of the mixture are esters of the fatty acids, then the last term in this equation must be increased by the number $R-1$, where R is the molar weight of the alkyl group. In the case of methyl esters, for example, the required value of the molecular weight b_{lm} is evidently

$$b_{lm} = 14(N+2m-2)-2l+46.$$

The alternative equations for mixtures of fatty acids are therefore

$$(39)\ldots\ldots \qquad \frac{I_t}{25400} = \frac{jp_{jk}}{14(N+2k)-2j+4} \qquad (j=1, \ldots n),$$

where

$$p_{jk} = 1-s=1-(p_{0k}),$$

and

$$(40)\ldots\ldots \qquad \frac{1}{E_t} = \frac{p_{jk}}{14(N+2k)-2j+4} \qquad (j=0, 1, \ldots n)$$

in which $p_{jk}=1$.

As will be easily apparent, these equations are merely more general forms of equations (26) and (28) given on page 13, part I; for if $j=a_1, a_2, \ldots a_n$, equation (39) becomes

$$\frac{I_t}{25400} = \frac{a_1 p_{a_1 1}}{14(N+2)-2a_1+4} + \frac{a_2 p_{a_2 2}}{14(N+4)-2a_2+4}$$

$$+ \ldots + \frac{a_n p_{a_n n}}{14(N+2n)-2a_n+4},$$

while equation (40) assumes a similar general form.

CALCULATIONS INVOLVING THIOCYANOGEN VALUES

The equation giving the thiocyanogen value of a mixture of esters of the fatty acids in terms of the thiocyanogen values of the individual components is easily written down from a consideration of the analogous equation (equation 34) involving iodine value. It is

$$(41)\ldots\ldots \qquad \frac{Y_t}{25400} = \frac{n_j p_{jk}}{b_{jk}} \qquad (j=1, 2, \ldots n)$$

$$p_{jk}=1-s$$

where Y_t is the thiocyanogen value of the mixture and the numbers n_j are the numbers of double bonds in the various esters (or acids) which add on thiocyanogen. The thiocyanogen value thus furnishes an additional constant describing a mixture of fatty acids or their esters.

In certain problems, however, as for example those dealing with the changes in composition of marine oils on hydrogenation, the information furnished by the thiocyanogen value together with the four other constants, I_t, E_t, s and E_s, is by no means all that could be desired, notwithstanding the fact that the introduction of the thiocyanogen value now gives five instead of four pieces of data describing the mixture of esters. This is partly a consequence of the uncertainties that arise in assigning values to the n's; for although the behaviour of thiocyanogen reagent towards mixtures of esters of oleic, linoleic and linolenic acids has recently been well established (Griffiths and Hilditch 1934), there is as yet little, if any, experimental basis for assuming that the reagent reacts in a similar way with esters of the corresponding unsaturated acids of the C_{20} and higher series. Still greater uncertainties arise when, as is the case with the majority of fish oils,

fatty acid residues containing more than three ethylenic linkages in the molecule are present. In problems concerned with the changes in composition of marine oils on hydrogenation, a second factor diminishing the practical usefulness of the equations involving the above data arises from the necessity of grouping the various esters according to unsaturation. This leads to the additional unknowns, namely, the equivalents b_{1c}, b_{2d}, . . . of the various groups of esters. When the grouping was according to carbon content as in the estimation of the composition of a mixture by the fractionation method of analysis, these equivalents were known quantities or could be readily assumed. Nevertheless, with certain not unreasonable assumptions, the equations involving I_t, E_t, s, E_s and Y_t, which have been derived in parts I and II of this series, will, as shown presently, supply considerable information regarding the composition, even of complex mixtures of esters such as those obtaining in fish oils.

CASE I. The mixture of esters consists of saturated and monoethylenic esters only. In this case equations (34), (41) and (35) become

$$(a)\ldots\ldots \qquad \frac{I_t}{25400} = \frac{p_{1c}}{b_{1c}} = \pi_{1c} = \pi_{1k} \qquad (k = 1, 2, \ldots m_1)$$

$$(b)\ldots\ldots \qquad \frac{Y_t}{25400} = \frac{n_1 p_{1c}}{b_{1c}} = n_1 \pi_{1c}$$

$$(c)\ldots\ldots \qquad \frac{1}{E_t} = \frac{s}{E_s} + \frac{1-s}{b_{1c}}$$

$$(d)\ldots\ldots \qquad 1 = s + p_{1c}$$

in which p_{1c} is the proportion by weight of monoethylenic esters and b_{1c} is the equivalent of these esters.

Equations (a) and (b), it will be observed, can be solved at once for n_1. If thiocyanogen reacts with monoethylenic esters of C_{14}, C_{16}, C_{20}, C_{22} and C_{24} acids in the same way as it does with oleic ester, n_1 should, of course, be equal to 1 for fish oils. If, on the other hand, $n_1 \neq 1$, then either this last assumption is wrong or there are unsaturated esters other than monoethylenic esters present in the mixture. The presence of quantities of diethylenic esters sufficient to cause an appreciable divergence in the value of n_1 from the theoretical value, 1, can be easily detected by an application of equations (a) and (c) of case II below, provided that both s and E_s have been determined; for then $\frac{s}{E_s}(=\pi_{0a})$ is known and by subtraction π_{2d}, the number of gram molecules of diethylenic esters per gram, is known. If diethylenic esters should prove to be present, the actual values of n_1 and n_2 can be calculated as shown under case II, provided data for samples of the same mixture of esters hydrogenated to different degrees of saturation are available. But if no diethylenic or more highly unsaturated esters are present, the actual value of n_1 and hence the test of the truth of the first assumption regarding the behaviour of thiocyanogen towards monoethylenic esters of the aforementioned acids follows, as stated above, from equations (a) and (b), case I.

It will thus be seen that in problems concerned with changes in composition on hydrogenation of complex mixtures of esters such as fish oils, the values of the n's in the simple cases I and II can be deduced from the experimental data and are consequently independent of any assumptions regarding the addition of thiocyanogen to mono- and diethylenic esters of acids other than oleic and linoleic acids.

An inspection of equations (a) . . . (d) shows that they can be solved for the unknowns p_{1c} and b_{1c} if:

(1) I_t and s are known;

(2) I_t, E_t and E_s are known;

and when the value of n_1 is known or can be assumed equal to 1, if

(3) Y_t and s are known;

(4) Y_t, E_t and E_s are known.

Hence in this case there are several alternative methods of checking the analysis.

CASE II. The mixture consists of saturated, monoethylenic and diethylenic esters only. In this case equations (34), (41) and (35) become

$$(a)\ldots\ldots \qquad \frac{I_t}{25400} = \frac{p_{1c}}{b_{1c}} + \frac{2p_{2d}}{b_{2d}} = \pi_{1c} + 2\pi_{2d};$$

$$(b)\ldots\ldots \qquad \frac{Y_t}{25400} = \frac{n_1 p_{1c}}{b_{1c}} + \frac{n_2 p_{2d}}{b_{2d}} = n_1\pi_{1c} + n_2\pi_{2d};$$

$$(c)\ldots\ldots \qquad \frac{1}{E_t} = \frac{s}{E_s} + \frac{p_{1c}}{b_{1c}} + \frac{p_{2d}}{b_{2d}} = \pi_{0a} + \pi_{1c} + \pi_{2d};$$

$$(d)\ldots\ldots \qquad 1 = p_{0a} + p_{1c} + p_{2d}.$$

If π_{0a} is known, that is, if s and E_s are known, the value of n_2 can be calculated, provided (1) n_1 is known or can be assumed equal to 1, or (2) data for two samples of the same mixture hydrogenated to different degrees of saturation are available. In either event π_{1c} and π_{2d} can be calculated by means of equations (a) and (c). The value of n_2 is then immediately forthcoming from the data in (1) and equation (b). But if the data in (2) are available, n_1 and n_2 can be solved for simultaneously in the two equations

$$\frac{Y_t}{25400} = n_1\pi_{1c} + n_2\pi_{2d}$$

$$\frac{Y_t'}{25400} = n_1\pi'_{1c} + n_2\pi'_{2d}$$

except in the special case when the determinant,

$$D = \begin{vmatrix} \pi_{1c}, & \pi_{2d} \\ \pi'_{1c}, & \pi'_{2d} \end{vmatrix} = 0.$$

In the latter event the molecular proportions of the two types of unsaturated esters in the two samples would be related by the equation

$$\frac{\pi_{1c}}{\pi_{2d}} = \frac{\pi'_{1c}}{\pi'_{2d}}$$

so that the relative proportions of the two types of esters would be constant in the interval, or in other words, the selectivity over the interval corresponding to the two samples would be zero.

It will thus be seen that there are in general two alternative methods of arriving at the actual values of n_1 and n_2, and consequently two ways of testing the truth of the assumption regarding the behaviour of thiocyanogen reagent towards both mono- and diethylenic esters of the acids other than oleic and linoleic acids mentioned under case I. If n_1 and n_2 are known and a knowledge of the weight proportions and equivalents of the two types of unsaturated esters is not essential, equations (*a*) and (*b*) afford a rapid method of following changes in these two types of unsaturation during hydrogenation. For this purpose, of course, it would be necessary to assume that n_1 and n_2 remain constant over the interval under consideration.

An interesting fact which may be readily deduced from equations (*a*) and (*b*) is that there is no functional relationship between the iodine and thiocyanogen values here except when $n_1 : n_2 = 1 : 2$. The Jacobian, $J = 0$ only if

$$J\left(\frac{I_t,\ Y_t}{\pi_{1c},\ \pi_{2d}}\right) = \frac{\partial(I_t,\ Y_t)}{\partial(\pi_{1c},\ \pi_{2d})} = 25400^2 \times (n_2 - 2n_1) = 0;$$

and this is so only if $n_1 : n_2 = 1 : 2$. This proves the statement, since the condition that there shall be a functional relationship between I_t and Y_t is that $J = 0$. Similarly it may be shown that there is no functional relationship between equations (*b*) and (*c*) unless $n_1 : n_2 = 1$. Hence if $n_1 = 1$, it follows that equations (*a*), (*b*) and (*c*) are independent unless $n_2 = 1$ or $n_2 = 2$. Theoretically both n_1 and n_2 should have the same value 1, if the assumption regarding the addition of thiocyanogen to mono- and diethylenic acids is correct. Equations (*b*) and (*c*) would not then be independent and so could not be solved for π_{1c} and π_{2d}. It is, however, always possible to select at least one pair of equations from (*a*), (*b*) and (*c*) from which the values of the two molecular proportions can be calculated. Equations (*a*) and (*c*), for example, can always be solved for these two unknowns.

Case III. The mixture consists of saturated, monoethylenic, diethylenic and triethylenic esters. The equations applicable to this case are

(*a*) ..... $$\frac{I_t}{25400} = \pi_{1c} + 2\pi_{2d} + 3\pi_{3e},$$

(*b*) ..... $$\frac{Y_t}{25400} = n_1\pi_{1c} + n_2\pi_{2d} + n_3\pi_{3e},$$

(*c*) ..... $$\frac{1}{E_t} = \pi_{0a} + \pi_{1c} + \pi_{2d} + \pi_{3e},$$

(*d*) ..... $$1 = p_{0a} + p_{1c} + p_{2d} + p_{3e}.$$

If it can be assumed that $n_1 = n_2 = 1$ and that $n_3 = 2$, the first three equations can be solved directly for π_{1c}, π_{2d} and π_{3e}. An alternative, and perhaps more reliable,

procedure in solving for the molecular proportions would be to assume the values of n_1 and n_2 from the sample of highest unsaturation treated under case II. By extrapolating π_{1c} (or π_{2d}) from the latter interval equations (*a*), (*b*) and (*c*) could be solved for n_3. Substitution of these values of the n'*s* in the equations would then furnish the numerical values of the unknowns (π'*s*) over the triethylenic interval, provided

$$J\left(\frac{I_t,\ Y_t,\ \Pi_u}{\pi_{1c},\ \pi_{2d},\ \pi_{3e}}\right) \neq 0.$$

The Jacobian is not zero if

$$25400\ (n_3+n_1-2n_2)\neq 0,$$

that is, if $n_3+n_1\neq 2n_2$. Hence if $n_1=n_2=1$, the equations can be solved for the unknowns provided that $n_3\neq 1$.

Here it should perhaps be emphasized that the equations given under case III above have, as yet, no secure experimental basis. In fact, the possibility of employing thiocyanogen values in the analysis of fish oils by the method of progressive hydrogenation outlined above is subject to the condition that experimental verification for certain postulates will be forthcoming. These postulates are:

(1) That thiocyanogen reagent reacts with esters of diethylenic acids other than linoleic, with triethylenic esters of C_{14}, C_{16}, C_{20}, C_{22} and C_{24} acids, and with esters of C_{14} to C_{24} acids inclusive containing more than three ethylenic linkages in the molecule.

(2) That thiocyanogen reacts differently with these acids than do the customary halogenating agents such as Wijs solution, and in general only partly saturates such acids.

And (3), that thiocyanogen does not react with the unsaturated esters enumerated in (1) in the special ways indicated under cases II and III.

It might be remarked *en passant*, however, that if thiocyanogen or some other reagent should be found to react with esters of unsaturated fatty acids in the manner described in the foregoing postulates, it would be possible by the method of progressive hydrogenation to estimate the proportions of the various types of unsaturated fatty acids in a fish oil with an accuracy at least comparable to that involved in the estimation of composition by the fractionation method of analysis. If, as seems probable (Charnley 1934b), the more highly unsaturated fatty acids in a fish oil disappear on hydrogenation at rates that are linear or approximately linear, then over the first stage of the reaction there would be available additional (linear) equations connecting the molecular proportions of these acids in successive samples.

CALCULATIONS INVOLVING REDUNDANT DATA

The calculations discussed in the previous section and those treated in part I of this series, it will be observed, are mainly concerned with the solution of a set of simultaneous linear equations. For the general case such a set of linear equations can be represented by the equations

$$a_{ik}x^k = A_i$$

where $i=1, \ldots, m$ and $k=1, \ldots, n$. When $m=n$, the solutions of these equations are given by

$$x^j = A_i a^{ij} \qquad (j=1, \ldots, n)$$

provided the determinant $|a_{ik}|$, or the matrix of the homogeneous equations derived from the set of linear equations corresponding to the general case does not vanish. The process of solving for the unknowns in the general case is thus perfectly straightforward.

The particular cases of these equations encountered in the analysis of given mixtures of fatty acids or their esters, however, are often slightly more complex. Frequently one equation in the set will be found to be a linear combination of two or more of the remaining equations; or one or more equations may contain terms having zero coefficients. If in fraction S11, part I, for example, it is assumed that unsaturated myristic ester is present in addition to unsaturated C_{16} ester, then the equations corresponding to this fraction are

(i)..... $$\frac{I_t}{25400} = \frac{jp_{jk}}{b_{jk}} \qquad (j=1)$$

(ii)..... $$\frac{1}{E_t} = \frac{p_{jk}}{b_{jk}} \qquad (j=0, 1)$$

(iii)..... $$\frac{s}{E_s} = \frac{p_{0k}}{b_{0k}}$$

(iv)..... $$1 = p_{jk} \qquad (j=0)$$

(v)..... $$s = p_{0k}$$

where the index k is to be summed over the values 1 and 2 throughout. An inspection of these five equations shows that they involve four pieces of experimental data and contain four unknowns. Evidently, then, one of the four pieces of data is redundant; but it is not clear from a cursory examination of the equations which piece of data is redundant.

To decide such questions it will usually be necessary to subject the equations to a more critical examination. In fraction S11, for example, the matrix of the coefficients of the unknowns, viz., p_{01}, p_{02}, p_{11} and p_{12}, is

$$A = \begin{vmatrix} 0 & 0 & \frac{1}{b_{11}} & \frac{1}{b_{12}} \\ \frac{1}{b_{01}} & \frac{1}{b_{02}} & \frac{1}{b_{11}} & \frac{1}{b_{12}} \\ \frac{1}{b_{01}} & \frac{1}{b_{02}} & 0 & 0 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 \end{vmatrix},$$

and the corresponding augmented matrix is

$$B = \begin{vmatrix} 0 & 0 & \frac{1}{b_{11}} & \frac{1}{b_{12}} & \frac{I_t}{25400} \\ \frac{1}{b_{01}} & \frac{1}{b_{02}} & \frac{1}{b_{11}} & \frac{1}{b_{12}} & \frac{1}{E_t} \\ \frac{1}{b_{01}} & \frac{1}{b_{02}} & 0 & 0 & \frac{s}{E_s} \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & s \end{vmatrix} .$$

The first 4-rowed minor of A is equal to

$$\begin{vmatrix} 0 & 0 & \frac{1}{b_{11}} & \frac{1}{b_{12}} \\ 0 & 0 & \frac{1}{b_{11}} & \frac{1}{b_{12}} \\ \frac{1}{b_{01}} & \frac{1}{b_{02}} & 0 & 0 \\ 1 & 1 & 1 & 1 \end{vmatrix}$$

which is equal to zero, since two rows are identical. The second 4-rowed minor of A, however, that is, the determinant,

$$\begin{vmatrix} \frac{1}{b_{01}} & \frac{1}{b_{02}} & \frac{1}{b_{11}} & \frac{1}{b_{12}} \\ \frac{1}{b_{01}} & \frac{1}{b_{02}} & 0 & 0 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 \end{vmatrix}$$

is not equal to zero, as will easily be found by expanding it. Also the square determinant $B=0$ only if $\frac{1}{E_t} - \frac{s}{E_s} = \frac{I_t}{25400}$, that is, only if $\frac{1-s}{E_u} = \frac{I_t}{25400}$, an equation which is true in this case, since monoethylenic esters only are assumed to be present. Hence the rank of B is equal to the rank of A $(=4)$ and it follows from the theory of determinants that equations (ii), (iii), (iv) and (v) determine uniquely the four unknowns and that equation (i) is a linear combination of the remaining equations (evidently equations ii and iii). It thus appears that either equations (i) or (ii) with the three remaining equations are sufficient to determine the composition of the fraction. Consequently, only three of the experimentally determined quantities are required in the analysis. Furthermore, the condition that the four pieces of data shall be harmonious is the condition that $B=0$, which, as shown above, is that $\frac{1-s}{E_u} = \frac{I_t}{25400}$.

CONCLUSION

The occurrence of redundant data such as those discussed in the previous section leads at once to the further problem of selecting one or more pieces of

experimental data from several such data. A typical example of this latter problem is furnished by the data of fraction S11, part I, of this series. These data illustrate the care that must frequently be exercised in applying formulae to the data encountered in fat analysis. In concluding this paper, therefore, it may perhaps be of value to outline briefly the procedure followed in this particular case.

If, as was done in part I, the assumption is made that the unsaturated ester present in this fraction is monoethylenic, and further, that this ester is almost entirely C_{16} ester, then the equations defining this fraction have the following indices:

$$\begin{array}{ll} \text{(i)} & j = 1 \\ \text{(ii)} & j = 0, 1 \\ \text{(iii)} & j = 0 \\ \text{(iv)} & j = 0, 1 \\ \text{(v)} & j = 0 \end{array}$$

where $k=1, 2$ for $j=0$ but $k=2$ for $j=1$.

From an inspection of these equations, or by more analytical means, it will be observed that, of the ten possible combinations of these equations three at a time, only two such combinations contain equations that are linear combinations of the remaining two in the set. These two sets are equations (i), (ii), (iii) and equations (i), (iv), (v). Hence it is possible to determine the values of the unknowns p_{01}, p_{02} and p_{12} by solving any one of the remaining eight sets of three, and for this purpose one of the following combinations of data will be required:

(*a*) I_t, E_t; (*b*) I_t, E_t, s; (*c*) I_t, s, E_s;

(*d*) E_t, s, E_s; (*e*) E_t, s; (*f*) s, E_s.

An examination of these data shows that it would in general be better to base the calculation on the data in (*a*). In other words it would be safer to discard the experimentally determined values of s and E_s. Since in this case $p_{12}=1-s$, the equation involving iodine value may be written

$$\frac{I_t}{25400} = \frac{1-s}{268}$$

and by taking derivatives

$$\Delta s = \frac{ds}{dI_t} \cdot \Delta I_t = \frac{-268}{25400} \cdot \Delta I_t = -0.0106\Delta I_t.$$

If, then, it can with reasonable safety be said that iodine values are accurate to 1 part in 150, ΔI_t becomes approximately 0.073 and by the second equation, $\Delta_s = -0.00077$, so that the calculated value of s is correct to 1 unit in the third significant digit. But even if the iodine value of fraction S11 were very much less accurate than 1 part in 150, say 1 part in 10, the error in the calculated value of s would be very slightly more than 1 unit in the second significant figure or 1 unit of a percent. This error is substantially less than the divergency between the calculated and experimental values of s (roughly 2 units percent).

The inadvisability of employing the calculated value of s for calculating the composition of this fraction becomes further evident from other considerations. For example, an attempt might be made to harmonize the two discordant values of s by questioning the original assumptions. If instead of monoethylenic C_{16} ester, C_{16} ester with an average unsaturation greater than 1 is assumed to be present, it becomes immediately evident that the discrepancy has only been increased; for the value of p_{12} or $1-s$ would in that case be decreased, and hence the calculated value of s would be increased.

The second assumption, viz., that the unsaturated ester is almost entirely C_{16} ester, rests securely upon the experimental fact that lead myristoleate (Hilditch 1927) is very soluble in 95 per cent alcohol. If, however, this piece of experimental data were wilfully disregarded and it was assumed that unsaturated myristic ester was also present, then the equations describing this fraction would be as shown in the preceding section. Owing to the fact that equation (i) in this case is a linear combination of equations (ii) and (iii) and that equation (i) or (ii) together with the three remaining equations are needed to determine the composition of the fraction, the five equations would be inconsistent unless the calculated value of s was employed in the calculations.

Finally, in the case of fraction S11 it seems reasonable to believe that the experimental value of s will be somewhat lower than the true value; for while the percentage of saturated acids as determined by oxidation methods will in general tend to be slightly high for the more unsaturated oils, owing probably to the presence of traces of semi-oxidized unsaturated acids which cannot be corrected for by iodine value, as Hilditch and Priestman (1931) have shown, magnesium soaps of lauric and myristic acids are appreciably soluble under the conditions of the Bertram procedure. The final figure for oils containing these acids will therefore be influenced by two opposing factors; and of these two factors, the second, due to the presence of C_{14} or lower acids will in general have the greater influence. In fraction S11 the first factor is negligible or practically so, but there is a comparatively high proportion of C_{14} ester. Hence it must be concluded that the experimentally determined percentage of saturated esters in this fraction will be lower than the true value.

REFERENCES

Brocklesby, H. N. and F. Charnley. *Contr. Canad. Biol. Fish.* **7** (41) (*Ser. C, Ind.* 13) 523, 1933.

Charnley, F. *Contr. Canad. Biol. Fish.* **8** (35) (*Ser. C, Ind.* 23) 509, 1934a.

Charnley, F. *Biol. Bd. Can. Pac. Prog. Rept.* **19**, 7, 1934b.

Griffiths, H. N. and T. P. Hilditch. *J. Soc. Chem. Ind.* **53** (11) 75, 1934.

Hilditch, T. P. Fats and waxes. D. Van Nostrand Co., 1927.

Hilditch, T. P. and J. Priestman, *Analyst* **56** (663) 354, 1931.

Thomas, T. Y. The elementary theory of tensors. McGraw-Hill Book Company, 1931.

The Food of Kingfishers and Mergansers on the Margaree river, Nova Scotia

By H. C. White
Biological Board of Canada
(*Received for publication March 7, 1936*)

ABSTRACT

The river, particularly its northeast branch, contains chiefly salmon and trout (*Salvelinus fontinalis*). *Kingfishers* shot along the northeast branch contained chiefly salmon remains, but also trout, sticklebacks and suckers. Disgorged kingfisher pellets showed the same food for the northeast branch but consisted chiefly of sticklebacks where that fish abounded. In feeding experiments young kingfishers consumed forty or more fish each per day. The numbers consumed by kingfishers on the Northeast Margaree in 1935 is estimated to have been 330,000 salmon, 50,000 trout, and 40,000 other fishes. They evidently fed upon the food most easily obtained. *American mergansers* were found frequenting the salmon and trout habitats, rearing their young on the smaller streams. Stomach analyses of 28 birds shot on the Northeast Margaree give as food 82.2% salmon, 6.3% trout, 11.5% other fishes. The estimated consumption on the Northeast Margaree for July to October, 1935, is 390,000 salmon and trout.

The subject of the relation of birds to fishes has been a controversial one, and there has unfortunately been a dearth of facts concerning the relation. During an investigation of the well known salmon river, the Margaree, in Cape Breton island, N.S., in the summer of 1935, an opportunity offered to study the food habits of the kingfisher and of the American merganser. The Margaree empties into the gulf of St. Lawrence, with a tidal portion about four miles (6½ km.) long. About four miles above the head of tide, it divides into two main branches, the Southwest, which arises from lake Ainslie about 12 miles (19 km.) away and the Northeast, which arises in high barrens about 25 miles (40 km.) to the northeast. The latter branch traverses a deep gorge, and then, for about 16 miles (28 km.), a fertile valley as much as two miles (3¼ km.) broad, before joining the other branch.

KINGFISHER

The belted kingfisher (*Megaceryle alcyon*) has been reported as feeding on a variety of animals. Bendire (1895, p. 36) reports that fish constitute a large part of its food but that it also eats crustacea, insects, frogs and lizards. Roberts (1932, p. 658) gives its food as consisting of: "largely small fish, also crawfish, mussels, frogs, lizards, small snakes, crickets, beetles, grasshoppers, water insects", and he also mentions mice, berries and other small fruits. Taverner (1934, p. 276) states that the kingfisher lives upon small fish.

Forbush (1927, p. 248) gives as its food largely the items mentioned above but also states that its food habits have not been fully investigated.

Whatever its food may be in other situations, no investigation seems to have been made regarding its food when living along such a salmon river as the Margaree.

The kingfisher is relatively abundant on the Northeast Margaree and its branches, but less common on the Southwest Margaree. The abundance of these birds on the Northeast branch is undoubtedly due to the fact that very favourable nesting sites are provided along this branch by the caving off of the alluvial banks of the stream.

At Garden pool on the Northeast branch the young kingfishers had been hatched some days before our arrival there on June 14. By the last of July, the young birds had left the nests and many of them were observed along the Northeast Margaree and its branches. For some time after leaving the nest it would appear that the young birds are dependent upon the old birds for their food. The young birds at this time either make many unsuccessful attempts at catching fish by diving from a height or their movements may be merely a form of play. Their first successful fishing seems to be accomplished by resting on a boulder or some other object a foot or two (ca. ½m.) above the water and plunging, somewhat clumsily, into the shallow water, catching fish which are smaller than those usually taken by the mature birds. The kingfishers of a single brood remain more or less together throughout the summer and may move away from the nesting region to places where food is more abundant. This migration of the broods was particularly noticeable on the Northeast Margaree.

For some days after the broods had left the nests the young birds were found near the nesting sites, but later in the summer there was a concentration of broods on Lake O'Law brook and particularly on that part of the Northeast Margaree above the alluvial bank region where they had nested. Since the nesting region had already been heavily fished this migration was evidently associated with the greater abundance of fish of a suitable size in the upper area of the stream. At the mouth of Trout brook, emptying into lake Ainslie, there was another concentration of kingfishers which was definitely associated with a great abundance of sticklebacks in that area.

After the nesting season 18 kingfishers were shot on the Margaree for stomach analyses. The data obtained from these analyses are given in table I. Of the 18 specimens secured 13 were taken on the Northeast Margaree and 5 at the mouth of Trout brook on lake Ainslie.

The stomachs of 3 of the 13 kingfishers taken on the Northeast Margaree were empty; 9 of them contained either salmon or trout remains and 1 contained a young sucker (table I). Also, these stomachs contained remains of 36 young salmon and 1 trout. The maximum number in a single stomach was that in a young kingfisher taken on August 8 in the area of concentration above the nesting region. The stomach of this bird contained the remains of 24 salmon fry-of-the-year, ranging from 4 to 6 cm. in length. The only other fishes found in this collection from the Northeast Margaree were the remains of 2 young suckers.

On August 17, 5 kingfishers were shot near the mouth of Trout brook a few rods from lake Ainslie where there was a concentration of kingfishers. Near the

mouth of this stream, trout, salmon and suckers of suitable size for kingfisher food were present but the predominating fish was the two-spined stickleback (*G. aculeatus*). These birds contained 15 sticklebacks, 2 salmon fry and 1 trout fry (table I). This observation, that the kingfisher may feed largely upon sticklebacks even though salmon and trout are present, confirms our previous observations made on a tame kingfisher which we reared at Forbes' creek, Prince Edward island (White 1927).

In the summer of 1933, Mr. R. W. Tufts collected 6 kingfishers on the Margaree river for stomach analyses. Only 3 of them contained food. 2 of these were from Hatchery brook and 1 from the Margaree river. Each of the 3 individuals contained both salmon and stickleback remains. The number of each species was not determined. In so far as these records go, they are in accord with our findings.

TABLE I. Contents of kingfisher stomachs, Margaree river, 1935

Place	Date	Numbers of Kingfishers adults	Numbers of Kingfishers juveniles	Salmon 1 yr.	Salmon fry	Trout	Stickle-backs	Other fish
Lake O'Law brook	July 30		1	—	—	—	—	1 sucker
Below First Forks	Aug. 2	1	2	3	2	1 (4¼ inch)	—	—
Below Gorge	Aug. 8	2	5	*	26			
Blue pool	Aug. 12	1		*				1 sucker
First Forks	Aug. 13	1		1	2			
Mouth Trout brook	Aug. 17	1	4		2	1 fry	15	

*Trout or salmon teeth.

Kingfishers do not digest the bones or larger scales of the fish which they eat. The digestive juices in the gizzard clean both the bones and scales very thoroughly and these are rolled into a pellet in the gizzard and then disgorged. We have frequently watched this act of disgorging the pellet by a tame kingfisher when it was accompanying us along the stream. The pellets are generally dropped by kingfishers from the perches which they use when feeding and may be found beneath those perches which do not overhang the water. The pellets are so compact that they do not readily break apart when first disgorged and may even fall upon and roll down a slanting rock face for several feet without breaking apart. However, after being subjected to the weather for a week or so they may become broken apart.

Regarding these pellets Bendire (1895) has stated: "The indigestible parts, such as bones and scales, are afterwards ejected in oblong pellets, which can be seen lying around their burrows or about their favorite perches."

Since the species of fish may be easily and positively identified from the bones and scales, we used these pellets extensively in making a study of the food of the kingfishers.

This method for identifying their food has been used by Nichols (1915, p. 27)

who records finding bones of golden shiners, gold fish, pickerel, sunfish and yellow perch and also crayfish remains in a mass of bones from a kingfisher's nest.

Disgorged pellets have been used in the study of the food of various other birds but their use in the study of the food of the kingfisher is exceptionally valuable, in that these pellets are usually left near the feeding places. Thus the investigator may determine that kingfishers have fed in a certain area even though there are no kingfishers present at the time. The time elapsing between the disgorging and the finding of the pellets may be judged from the condition of the pellets. On the Margaree we were able to determine from pellets collected in August that certain pellets had been disgorged early in the season, since the yearling salmon scales in the pellets showed that the fish had been killed when their growth for that summer was indicated on the scale by only 1 or 2 circuli instead of the 10 or 12 usually present by August. 182 pellets were collected and analyzed. In these analyses the bones found to be most useful both for identification of the species and determining the number of individuals were the maxillary, dentary and parasphenoid bones. By comparing the measurements of these bones with bones prepared from known specimens, the length of the fish could be estimated. The ages of most of the fishes could be readily determined by scale reading as the scales were thoroughly cleaned and in excellent condition for reading.

Collections of pellets were made at nine representative stations along the Northeast Margaree and also from two stations on Trout brook, tributary to the Southwest Margaree. The analyses of the pellets from these stations are given in table II.

TABLE II. Constitution of kingfisher pellets collected on Margaree river, N.S., 1935.

Place	Date	No. pellets	No. salmon			No. trout	No. sticklebacks	Other fish
	1935		2 yr.	1 yr.	fry			
Northeast Margaree								
Lake O'Law brook	Aug. 10	10		18	2	6	7	1 killifish
Above Garden pool	Aug 6	5		6	6	2	4	
Cranton bridge	Aug. 16	2		2	—	—	1	
Ingrams bridge	Aug. 10	12		19	11	2	3	
Big slide	Aug. 6	21	2	39	—	3	3	
Big intervale	Aug. 8	30		64	4	31	8	2 suckers 1 killifish
Stewart's brook	Aug. 16	21		36	17	13	4	
Head of settlement	Aug. 16	17		23	1	7	0	
First Forks in gorge	Aug. 13	9	1	14	—	4	0	
Southwest Margaree								
Mouth Trout brook	Aug. 17	37		1	5	1	128	
Mile up Trout br.	Aug. 17	6		2	2	10	4	

Note: Detailed tables for various collections are available for reference from the Biological Board of Canada.

128 pellets collected from the Northeast Margaree stations contained the remains of 278 salmon (237 yearling or older and 41 fry-of-the-year) 45 trout (*Salvelinus fontinalis*) 29 sticklebacks (*G. aculeatus*) 2 young suckers (*C. commersonii*) and 1 killifish (*Fundulus diaphanus*). Calculating these results on a numerical basis gives salmon 78.3%, trout 12.7%, other fish 9%. That is, 91% of their food consisted of commercial and game fish. The character of the Northeast Margaree varies considerably between that found at Garden pool with its broad flood plains and the character of the stream in the rocky gorge above settlement. This variation of character is revealed in the percentages of trout and salmon, sticklebacks, killifish and suckers found in the pellets collected from the various regions. At the mouth of Lake O'Law brook, with its broad flood plain and consequently more numerous back waters and flood-plain pools, sticklebacks were found in 50% of the pellets. At Big intervale, where the flood plain is also wide, sticklebacks were present in 30% of the pellets. Between these two areas at Big slide where the valley is constricted, stickleback remains were found in only 14% of the pellets. In the upper portion near the head of settlement and in the rocky gorge no remains of sticklebacks or fishes other than salmon and trout were found in the pellets.

37 pellets collected on Trout brook about 20 rods (100 m.) above the point where it empties into lake Ainslie give an entirely different picture. These pellets contained the remains of 128 sticklebacks, 6 salmon and 1 trout. In this particular location 95% of the food was sticklebacks and only 5% salmon and trout. There was a concentration of sticklebacks in this part of the stream as large numbers of them had come in from the lake. There was also an evident concentration of kingfishers here and the piles of bones from disgorged pellets showed that they had been feeding there for some time. The scarcity of salmon and trout remains in these pellets did not indicate an actual scarcity of these fishes there but rather a relative scarcity.

Between one-half and one mile(1-2 km.) up Trout brook 6 pellets were found and a number of kingfishers were observed. Pellets in this area were hard to find because most of the perches were overhanging the water. However the few pellets collected here, in the short time at our disposal, show that the kingfishers on this area of the stream were feeding largely upon young trout. These 6 pellets contained 4 sticklebacks, 10 trout (yearling or older), 1 trout fry, 2 yearling salmon and 1 salmon fry.

While collecting pellets, on two occasions dead salmon were found beneath the kingfisher perches. From the location of the fish and from the fact that I had observed kingfishers drop other fish which were too large for them to swallow, it seemed evident that these salmon had been dropped by kingfishers.

"Bird marks" or the scars left on fish which have been struck by birds, are common on trout and salmon. The marks left by the kingfisher differ from those made by the great blue heron or those of the merganser (figure 1). We have found heron marks frequently on trout, generally in the region of the dorsal fin. and kingfisher marks on parr and smolts in similar places. We have also found merganser scars on several trout and salmon parr in the region of the caudal

peduncle. Merganser scars are probably less common because unlike the kingfisher or heron, the merganser is generally able to pursue a fish and recapture it.

In the higher bank of Garden pool there was a kingfisher's nest which was opened a number of times for observation. This nest contained seven young birds. Previous to the breaking of the flight feathers from their sheaths, two of these young birds, a male and a female, were removed from the nest and were hand-reared. Success in rearing a young kingfisher depends largely upon having a liberal and constant supply of fresh fish to feed them. The young birds were fed largely upon young suckers which were seined from the river. These birds became very tame and appeared physically normal in every way.

By weighing the food of these birds before they were able to fly, it was found that they consumed from one to one and three quarter times their weight in fish

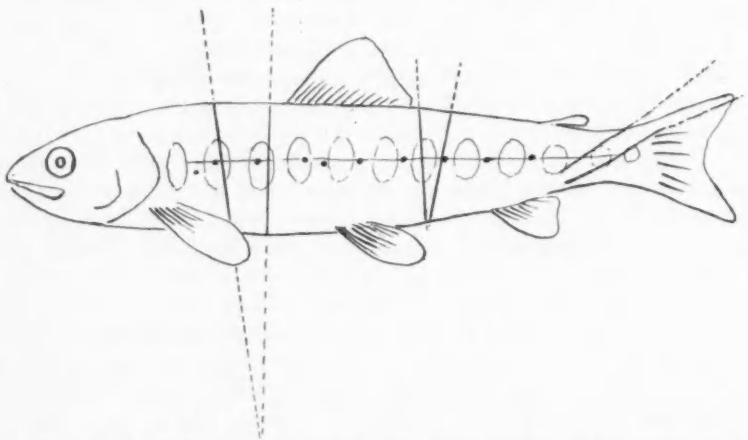


FIGURE 1. Drawing of 16 cm. salmon parr showing characteristic "bird-marks" or scars left on trout and salmon by great blue heron, kingfisher and merganser (in order from left to right.)

every day. 40 or more yearling suckers (from 4 to 7 ounces (100 to 200 grams) of fish) were required for each bird daily. The accompanying photograph (figure 2) of the young female bird shows also the daily supply required for one young bird. Like other fish-eating birds, their digestion is very rapid. The development of the young birds left in the nest did not differ from that of the hand-reared birds. After the tamed birds had begun to fly, at intervals they returned to us from the stream for food.

FEEDING

Young birds, when first beginning to fish, may strike from a position only a foot or two (½ m.) above the water. Small fish in shallow water are taken by them. This was the method observed in the feeding of the young kingfishers and was further verified by the finding of 24 salmon fry remains in the stomach of a young bird. Salmon fry-of-the-year are not often taken by the adult birds. Kingfishers begin their fishing at daybreak and continue throughout the day. It

would appear that ordinarily a kingfisher on suitable fishing grounds has little difficulty in securing food for itself, since a pair of adult birds are able to catch enough food for their own requirements besides feeding a nest of five or seven young birds. Feeding a nest of seven young birds at the rate which our tame birds consumed fish would require 280 fish daily, averaging about 6 cm. in length. However, since most of the fish captured by the adult birds are much more than 6 cm. in length, the number of fish consumed daily by a nest of 7 birds is probably not

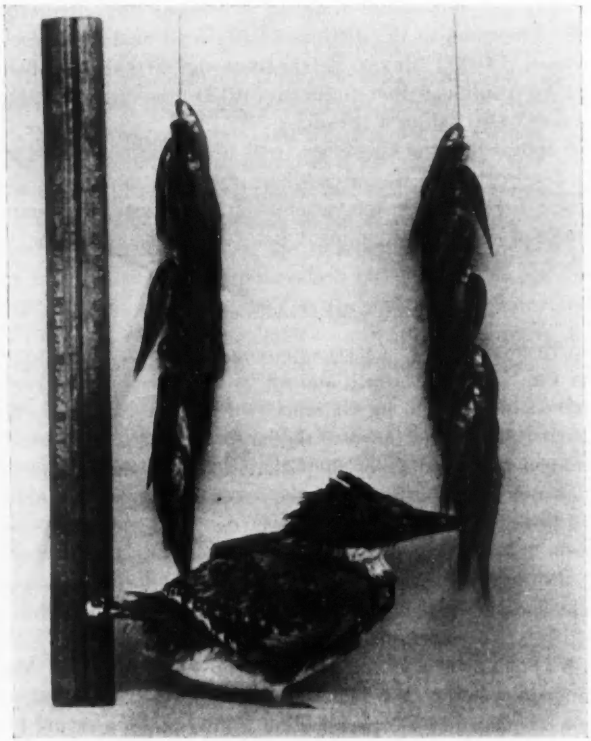


FIGURE 2. Young kingfisher, Northeast Margaree river, July 22, 1935, showing 40 of the 51 young suckers consumed by it that day.

more than 150 fish. Apparently there are times when kingfishers have difficulty in securing all the food they desire. During heavy freshets, when the water is turbid or during heavy gales or heavy rain, it would appear that they have difficulty in catching enough food. The bird which we reared at Forbes creek, P.E.I., although he ordinarily caught his own supply of fish and did not visit our tent, would come repeatedly to the tent for food during a rain or heavy wind. Moreover, kingfishers may be found fishing in small streams far into the thick woods during

freshets, high winds or heavy rain. They do not often frequent such places during fair weather or low water.

There are 30 miles (50 km.) of stream on the Northeast Margaree and its tributaries suitable for the nesting of kingfishers, and we have found that there was approximately one nest per mile of stream. Each nest consists of from seven to nine birds, including the old birds. Allowing the minimum of seven birds gives an estimated total of 210 kingfishers on this stream system. If these birds consume 20 fish per day, half the number taken by the tame birds, for 100 days, which is approximately the time from fledgling period to migration, they would kill 420,000 fish. According to the findings of the food analyses these would consist approximately of 330,000 salmon, 50,000 trout and 40,000 other fishes.

It might be mentioned that Sullivan (1912) has estimated that one pair of kingfishers takes 6,000 fish in a season.

It would appear that the kingfisher feeds upon the food that it can most easily obtain. On the Northeast Margaree where the predominating fishes are salmon and trout, these fishes were taken, whereas at the mouth of Trout brook, where the sticklebacks were the predominant fish, they constituted the major part of this bird's food.

MERGANSER

The American merganser (*Mergus merganser americanus*) occurs throughout the length of the Northeast branch and on its tributaries. The females generally nest and rear their young along the smaller branches but as the young become larger they are often brought down to the larger part of the stream. We observed females with young several miles up Galant brook, Lake O'Law brook and on Second Fork brook. While the young are small they are not so much in evidence as later when flocks of fifty or more large birds, yet unable to fly, may be seen as they scuttle on the surface of the river. Throughout the summer non-nesting (yearling?) birds were present in considerable numbers in the estuary but few of these came above tidal water. During June, many pairs or small flocks were found on the main part of the Northeast Margaree.

Mr. B. N. Smallman who was stationed for observations at Margaree Forks (i.e. the junction of the Northeast and Southwest branches) has reported mergansers on the Northeast branch within a quarter of a mile (½ km.) of the Forks almost daily. However he observed none throughout the summer on the Southwest branch. The Southwest Margaree contains many more eels, sticklebacks, killifish and suckers than the Northeast Margaree and yet the mergansers seem to prefer the Northeast branch, where there is little other than salmon and trout available.

Lake Ainslie at Trout river contains an abundance of small fishes of a considerable number of species and yet all the mergansers observed in that region were found up Trout brook where the only fishes were salmon and trout. On June 20 we found two female mergansers about a mile (1½ km.) up this brook and on July 20 Dr. A. G. Huntsman reported a female with a brood of "well-grown" young about two miles (3 km.) up the brook.

Taverner (1934, p. 110) states that mergansers "tend to take the food most easily obtained". This being the case, it is important to consider what food is available in the waters where their feeding is considered of possible importance, and at the same time to determine what their food in such places actually is. There has been little attempt made to systematically determine the merganser's food, the best work being that of Munro and Clemens (1934, p. 45) in British Columbia. In the waters with which they were concerned there are more species of fishes and of kinds other than those found in the Northeast Margaree. There appears to be no account of the merganser's food in waters comparable to those of the Margaree system.

On Aug. 12 and 13 we made a trip into the mountainous part of upper Northeast Margaree river above the settlement. In this part of the stream several flocks of fledgling mergansers were observed but the fact that mergansers had fed heavily along that portion of the stream examined in a two days' trip was revealed by the extent of the manure splashes along the shores and on the protruding rocks. In the lower part of the Northeast branch in an area where mergansers had been kept under control by shooting during the summer, numbers of young salmon and trout could be observed by direct observation but during the two-day trip along this upper portion of the stream where the evidence of merganser feeding was so obvious we did not see any young salmon by careful inspection of the bottom of the pools. The only parr which we found were concealed beneath stones.

During the summer 28 mergansers were shot for stomach analyses. These were taken at various points between the head of tide water and Second Forks brook, three miles (5 km.) above the settlement, in the rocky gorge. 5 of these birds had empty stomachs but identifiable food remains were found in 23. The data for these analyses are given in table III. The food found in these included 65 salmon (56 yearling, 9 fry), 5 trout (8 to 14 cm.), 5 *Fundulus* sp., 4 Gasterosteidae, water striders and a few vegetable fragments. The insect and vegetable matter found in these stomachs was negligible in amount. Calculating the percentages of fishes found in their stomachs on a numerical basis gives the following results: salmon 82.2%, trout 6.3, killifish 6.3, stickleback 5.2. That is, trout and salmon constituted 88.5% by number. In percentage by bulk the salmon and trout content would be very much higher since the sticklebacks and killifish are much smaller than the average trout or salmon taken by these birds. The average size of the trout was also considerably larger than that of the salmon.

In the Northeast Margaree the only fish occurring in any abundance, other than the salmon and trout, is the common sucker and these are mostly found in the lower part of the stream. The other fishes which occur in very limited numbers are eels, fresh water killifish, (*F. diaphanus*) and sticklebacks (*G. aculeatus* and rarely *P. pungitius*). Since the merganser is essentially a fish-eating bird, at least after it is half grown, and since many nest and live throughout the year on the Northeast Margaree, it becomes highly probable, that, as these analyses indicate, the dominant fish in these waters must constitute its main food.

We have no method of estimating accurately the number of mergansers on the Northeast Margaree but one flock which we encountered near the head of settlement on August 8 contained upward of 50 birds. At this time we knew of the presence of several other smaller flocks so that a very conservative estimate of the number of mergansers reared on the Northeast Margaree (1935) would amount to at least 100 birds. Elsewhere we have killed mergansers containing more than half a pound (250 grams) of fish which would represent only part of

TABLE III. Contents of merganser stomachs, Northeast Margaree river, 1935

Place	Date 1935	No. of mergansers	Salmon yls.	Salmon fry	Trout	Other fish	Miscellaneous
Garden pool	June 18	1 ad.	3				
Garden pool	June 20	1 ad. ♀	4			1 *F. diaphanus*	
Doyle's bridge	June 28	2 ad. ♀♀	16	—	—	—	Veg. frags.†
Garden pool	July 2	1 ad. ♀	9	—	1-(14 cm.)		
Doyle's bridge	July 3	1 —	1	1		3 *P. pungitius* 1 *C. commersonii*	
Head of tide	July 5	2 imm. ♀ ♀	—	—	—	4 *Fundulus* sp. 1 Gasterosteidae	
Garden pool	July 16	1 imm. ♀	2				
Marg. Forks	July 28	2 —	4		1-(10 cm.)		
Head of settlement	Aug. 8	5 jv.	4		2-(15 cm.) (10 cm.)	—	Veg. frags.
Second Forks	Aug. 13	1 jv.	2	—	—	—	2 Lepidoptera lv. 1 Gerrid
First Forks	Aug. 13	2 jv.	3	—	—	—	Veg. frags. 3 Gerrid
Wash pool	Aug. 16	2 jv. ♂♂	5	1	—	—	Gerridae frags.
Cranton bridge	Aug. 16	1 jv.*	—	7	—	—	1 Gerrid
Garden pool	Aug. 20	2	2		—	—	Veg. frags. Gerrid

*Less than half grown.
†Veg. frags.—small pieces of roots and grass.

their daily consumption. If these birds on the Northeast Margaree consume per day but half a pound of yearling salmon or trout fingerlings averaging 4 to the ounce (28 grams) i.e. 32 fish, in the period July to October they would consume 390,000 fish. Since mergansers are found there throughout the year and with considerable numbers, even feeding through holes in the ice during the winter, it seems probable that their consumption of salmon and trout fingerlings and yearlings must be in excess of half a million.

REFERENCES

BENDIRE, CHARLES. Life histories of North American birds. *Smithsonian Inst. U.S. Nat. Mus. Spec. Bull.*, 1895.

FORBUSH, E. H. Birds of Massachusetts and other New England states. Vol. 2. Boston, 1927.

MUNRO, J. A. AND W. A. CLEMENS. Canad. Field-Nat. **48** (3) 1934.

NICHOLS, J. T. *Copeia*, Aug. 1915.

ROBERTS, T. S. The birds of Minnesota. Minneapolis, 1932.

SULLIVAN, R. H. *Kansas State Agri. Coll. Agri. Educ.* **3** (7) 1-47, 1912.

TAVERNER, P. A. *Bull. Nat. Mus. Can.* **72**, 1934.

WHITE, H. C. *Contr. Canad. Biol.* N.S., **3** (15) 367-375, 1927.

An Investigation of the Life History and Propagation of the Sockeye Salmon (*Oncorhynchus nerka*) at Cultus Lake, British Columbia. No. 5. The Life history cycle of the 1926 year class with Artificial Propagation involving the liberation of free-swimming fry.

By R. E. Foerster
Biological Board of Canada
(*Received for publication March 9, 1936*)

ABSTRACT

From 1,949 sockeye salmon females in the run of 1926, 8,770,000 eggs were available. Of these approximately 1,174,000 (13.4%) were lost through 261 females dying before stripping. Since part of this loss was undoubtedly due to conditions imposed by the investigation, a second set of percentages based on egg content of the fish stripped is given. The true values lie between the two. Fry liberated in the spring of 1927 amounted to 5,916,500 (67.5% of total available eggs and 77.9% of eggs available for stripping). From these there migrated to sea 336,173 yearlings and 8,000 two-year-olds, representing 3.9% of total eggs and 4.5% of eggs available for stripping, and but 5.8% of total fry liberated. The yearling seaward migrants, which showed no change in size as the migration proceeded, were appreciably smaller than those in the 1927 migration, thus exhibiting an inverse relationship to the presumed populations in the lake during the first year. Scale-ring counts for the two age groups were made and rates of growth computed from scale measurements. Returning adults consisted of: 3_2 group (1929)—9 males; 4_2 group (1930)—2,327 males + 5,300 females; 5_2 group (1931)—149 females, a total of 7,785 adults—representing 0.09% of total eggs and 2.3% of seaward migrants. From 99,700 migrants marked by the removal of the adipose and both ventral fins, 1,340 adults (1.34%) returned to Cultus lake and 341 (0.34%) were taken in commercial fishing areas. The latter are not considered a complete recovery.

The investigation of the life history and propagation of sockeye salmon at Cultus lake, British Columbia, was undertaken primarily to determine the relative efficiencies of both natural and artificial methods of propagation. As outlined in the first paper of this series (Foerster 1929a) each method was to be tested independently several times and coincidentally data pertaining to the life history of the species throughout the life-cycle were to be assembled. The first test of natural propagation was made in the season of 1925-26 and reported upon in conjunction with the remainder of the life-cycle, 1925-1930, in no. 4 of this series (Foerster 1934). The first test of artificial propagation, that involving distribution of free-swimming fry, was made in the 1926-27 season and the results are reported upon in the present paper together with the data relating to the complete life cycle. Preliminary information concerning the adult spawning run of sockeye in 1926 and the distribution of fry was reported in paper no. 2 of this series (Foerster 1929b) and the data are briefly reviewed herein.

SPAWNING

As previously described (Foerster 1929b) a total of 5,071 adult sockeye arrived at the counting fences, of which 3,122 were males and 1,949 were females. The males were thus substantially in excess of the females, 8 : 5, quite different to the preceding 1925 run when 1,540 males and 3,883 females produced a preponderance of females. The larger number of males in 1926 was made up, in part, of small precocious three-year-olds.

Stripping commenced on September 21 and ended December 16 but the greater part took place during November. The average number of eggs contained in a female was found, by examination of a representative sample, to be 4,500 and the total egg content of the entire run, or as henceforth expressed, *the total available eggs,* based on 1,949 females, *was therefore 8,770,000.*

While the sockeye were being held below the weir to attain maturity and also during the stripping operations, losses occurred, amounting among the females, to 261 individuals. The egg loss so represented amounted to 261 x 4,500 or approximately 1,174,000 eggs—*13.4 per cent of the total available eggs.* As explained in the previous report (no. 2) a portion of this loss was probably caused by the enforced retention in the stream below the weir and not directly chargeable to normal artificial propagation methods. Therefore allowances for this unavoidable circumstance have been made and a second set of calculations have been drawn up excluding the loss due to dead females and applying only to eggs available for stripping. The two sets of percentages will be carried throughout this and subsequent reports and the true value lies somewhere between them.

Of the 1,949 females contained in the 1926 run, 1,688 only were stripped by the expression method. From these a total of 1,688 x 4,500, or 7,596,000 eggs, was available for stripping, but a collection of only 6,487,000 was obtained. The difference, 1,109,000, represents the number of eggs left within the body cavity of the females after stripping, *a loss of 12.6 per cent of total available eggs or 14.6 per cent of eggs available for stripping.*

The 6,487,000 eggs collected were removed to the Cultus lake hatchery, hatched and the resulting fry reared to the free-swimming stage for liberation into the lake. During the latter part of February, when the eggs had reached the "eyed" stage and could be safely handled, a count was made of the eggs in the hatchery troughs, which formed the basis for completing the hatchery records. Losses in dead eggs were recorded regularly and amounted to 490,675 up to the time of hatch and 79,825 after hatch, a total of 570,500 or *6.5 per cent of total available eggs and 7.5 per cent of eggs available for stripping.*

There remained for liberation into Cultus lake a total of 5,916,500 free-swimming fry, representing *67.5 per cent of total available eggs or 77.9 per cent of eggs available for stripping.* These fry were liberated into the lake during April and May, 1927, small allotments being taken out in shipping cans each day by row-boat or canoe and released along the shores at different points.

DOWN STREAM MIGRATION OF THE YOUNG

In this investigation the degree of efficiency of any propagational method is based upon the total number of young sockeye which are produced from the total eggs contained in all females counted or from the total eggs available for stripping and which migrate seaward. The losses occurring from spawning of eggs to the seaward migrant stage are the factors which determine the level of efficiency. The sockeye migrate to sea either as fry, yearlings or two-year-olds and hence counts of each age group are necessary. They are dealt with below.

Fry Migrants.

No sockeye fry were encountered at the counting fence, described in no. 3 of this series (Foerster 1929c), in the spring of 1927, the year of liberation. The fact that the fry were only being released into the lake during the months of normal seaward migration probably accounted for the lack of fry migrants.

Yearling Migrants.

Yearlings resulting from the 1926-27 hatchery operations constituted the major portion of the down-stream migration in the spring of 1928 and the counts of migrants were made as in table I. Commencing on March 19 a few fish appeared each day until April 6 when the numbers began to increase, culminating in a peak run of 55,488 individuals on April 29. Thereafter daily arrivals dwindled, the last being counted on June 11.

Temperature readings taken daily with ordinary centigrade thermometer at the counting fence indicated that, as in 1927, (Foerster 1929c), the migration commenced with a creek temperature of 6°C., reached a peak at around 10°C. and dropped off as the water warmed to above 11°C. The creek temperatures do not, of course, accurately reflect the conditions in the lake above, being largely a record of epilimnial trends, but they provide an interesting correlation. The effect of sunlight or bright weather was again exemplified by a diminution in the daily run on dull, cool or rainy days and a very appreciable increase in the succeeding bright warm days.

NUMBER OF YEARLING MIGRANTS AND PERCENTAGE SURVIVAL.

The total 1928 migration consisted of 337,895 sockeye. As described in paper no. 4 of this series (Foerster 1934, pp. 5 and 6) the two-year-old individuals in the run were the product of the previous cycle's spawning, 1925, and were estimated at 1722. The yearlings thus numbered 336,173 and, being the product of the 1926-27 artificial propagation, present, therefore, *a survival of 3.8 per cent of the total 8,770,000 eggs available and 4.4 per cent of the 7,596,000 eggs available for stripping.*

To define the statistical accuracy of the determination of yearlings from the total migration of 1928, the method devised by Ricker (unpub. MS., to appear in *Biometrika*) for obtaining the fiducial limits or limits of confidence, has been used. From the latter's table reproduced here as table II, making use of the 14 two-year-

TABLE 1. Down-stream migration counts for 1928.

Date	Temp. °C.	Number of migrants	Date	Temp. °C.	Number of migrants
March 19	6.0	12	May 1	9.0	749
21	6.5	4	2	9.0	5,644
22	6.0	12	3	9.0	13,965
23	6.0	14	4	9.5	6,907
24	6.0	31	5	10.0	17,726
25	6.0	53	6	12.0	6,679
26	6.0	73	7	11.5	2,000
27	6.0	1	8	11.0	813
28	6.0	85	9	12.5	682
29	6.0	3	10	12.5	642
30	7.0	4	11	13.5	200
31	6.5	5	12	14.0	117
April 1	6.0	2	13	13.0	340
2	6.0	42	14	13.0	827
3	6.5	40	15	14.0	214
4	6.0	47	16	14.5	54
5	6.0	43	17	14.5	94
6	6.0	493	18	15.0	100
7	6.0	475	19	15.5	149
8	6.0	2,606	20	16.0	123
9	9.0	1,657	21	17.0	246
10	8.5	1,275	22	16.5	55
11	8.5	1,616	23	16.5	269
12	8.0	1,315	24	17.0	355
13	8.0	7,472	25	18.0	174
14	8.0	1,912	26	18.0	282
15	8.0	9,214	27	18.0	43
16	8.0	5,167	28	18.0	55
17	7.5	6,685	29	16.5	108
18	8.0	3,538	30	16.0	51
19	9.0	8,131	31	16.0	172
20	8.5	17,172	June 1	16.5	5
21	8.5	33,856	3	17.5	16
22	9.0	8,411	4	17.0	46
23	9.0	30,919	5	17.0	17
24	9.0	6,899	6	16.0	10
25	9.5	5,960	8	17.0	21
26	9.5	25,377	10	17.0	15
27	11.0	13,603	11	17.0	4
28	10.0	11,478			
29	10.0	55,488			
30	10.0	13,550			
			Migrants counted.....		335,709
			Number in sample.....		2,186
			Total migrants.....		337,895

olds in the sample rather than the 2,172 yearlings, it is found that the fiducial limits of occurrence of two-year fish, with a confidence coefficient of 0.99 are 6.2 and 26.7 or, on the basis of a run of 337,895 and a sample of 2,186 are 958 and 4,127

individuals. The limits for yearlings would therefore be 336,937 and 333,768 and *calculated as survival from total available eggs the percentage would vary from 3.84 to 3.80 and for eggs available for stripping, from 4.43 to 4.39.* The statement above, therefore, indicating for the yearling migration generally a survival of 3.8

TABLE II. Confidence or fiducial limits for the Poisson frequency distribution. Calculated by W. E. Ricker as an extension of the method of Clopper and Pearson (1934). Applicable only where P or $^{x}/_{n}$ is less than 0.05 or preferably 0.01.

Confidence coefficient	0.99		0.95			0.99		0.95	
x	Lower limit	Upper limit	Lower limit	Upper limit	x	Lower limit	Upper limit	Lower limit	Upper limit
0	0.0	5.3	0.0	3.7					
1	0.0	7.4	0.1	5.6	26	14.7	42.2	17.0	38.0
2	0.1	9.3	0.2	7.2	27	15.4	43.5	17.8	39.2
3	0.3	11.0	0.6	8.8	28	16.2	44.8	18.6	40.4
4	0.6	12.6	1.0	10.2	29	17.0	46.0	19.4	41.6
5	1.0	14.1	1.6	11.7	30	17.7	47.2	20.2	42.8
6	1.5	15.6	2.2	13.1	31	18.5	48.4	21.0	44.0
7	2.0	17.1	2.8	14.4	32	19.3	49.6	21.8	45.1
8	2.5	18.5	3.4	15.8	33	20.0	50.8	22.7	46.3
9	3.1	20.0	4.0	17.1	34	20.8	52.1	23.5	47.5
10	3.7	21.3	4.7	18.4	35	21.6	53.3	24.3	48.7
11	4.3	22.6	5.4	19.7	36	22.4	54.5	25.1	49.8
12	4.9	24.0	6.2	21.0	37	23.2	55.7	26.0	51.0
13	5.5	25.4	6.9	22.3	38	24.0	56.9	26.8	52.2
14	6.2	26.7	7.7	23.5	39	24.8	58.1	27.7	53.3
15	6.8	28.1	8.4	24.8	40	25.6	59.3	28.6	54.5
16	7.5	29.4	9.2	26.0	41	26.4	60.5	29.4	55.6
17	8.2	30.7	9.9	27.2	42	27.2	61.7	30.3	56.8
18	8.9	32.0	10.7	28.4	43	28.0	62.9	31.1	57.9
19	9.6	33.3	11.5	29.6	44	28.8	64.1	32.0	59.0
20	10.3	34.6	12.2	30.8	45	29.6	65.3	32.8	60.2
21	11.0	35.9	13.0	32.0	46	30.4	66.5	33.6	61.3
22	11.8	37.2	13.8	33.2	47	31.2	67.7	34.5	62.5
23	12.5	38.4	14.6	34.4	48	32.0	68.9	35.3	63.6
24	13.2	39.7	15.4	35.6	49	32.8	70.1	36.1	64.8
25	14.0	41.0	16.2	36.8	50	33.6	71.3	37.0	65.9

per cent of total available eggs and 4.4 per cent of eggs available for stripping may be considered reasonably accurate.

SIZE OF YEARLING MIGRANTS.

The size trends of the yearling migrants of 1928 are indicated in tables III and IV for length and weight respectively.

TABLE III. Distribution according to length in cm. of samples of yearling migrants of 1928 taken during periods indicated

Length cm.	April 2 3	4 −11	12 13	14 −16	17 −19	20 −22	23 24	25 26	27 28	29	April 30 to May 1	May 2 3	4 −6	7 −28	Total
6.4			1										1		2
6.5			1			1									2
6.6					1			1							2
6.7	1	2	2		1					1			1	1	9
6.8			2		2	2	1		1	3		1	1		13
6.9		1	2		1	4	1		1	1	1	1	1	2	16
7.0	1	3	2	1			1			2			5	2	17
7.1	1	2	3	1		1	3		1	1	1	1	3	3	21
7.2	1	8	7		3	9	1		2	1	2	2	5	6	47
7.3		3	8	7	7	13	4	5		12	2	2	7	4	74
7.4		3	4	2	4	10	4	1	6	6	4	4	8	1	57
7.5	1	14	12	5	4	9	10	6	10	7	6	3	10	6	103
7.6	2	8	10	6	5	14	6	8	6	14	3	1	10	5	98
7.7	7	6	8	9	10	14	9	4	9	20	9	6	11	3	125
7.8	7	5	6	14	9	14	12	11	5	10	8	5	6	10	122
7.9	2	11	13	14	6	14	13	7	8	15	15	8	15	6	147
8.0	5	15	19	9	14	21	12	23	11	16	19	9	13	10	196
8.1	5	6	12	5	4	17	16	12	11	17	10	22	10	9	156
8.2	4	8	12	12	10	4	11	18	7	12	11	15	15	11	150
8.3	2	9	21	14	10	12	21	13	12	15	18	12	13	5	177
8.4	4	11	7	19	6	9	10	15	12	7	11	20	13	6	150
8.5	2	10	8	8	8	7	9	8	12	8	13	8	11	9	121
8.6	3	4	6	9	3	4	10	8	7	8	14	15	5	12	108
8.7	2	7	3	4	5	6	9	6	6	3	6	6	3	6	72
8.8	2	2	7	5	4	2	6	1	6	4	9	3	1	7	59
8.9		1	5	3	5		3	2	4	3	8	4		2	40
9.0		1	3	3	1	2	1	3	3		6	2	1	7	33
9.1	1	1	2	1			3	2	6	2	2	2		2	24
9.2				1	1		2	1	1				1	2	9
9.3			1	1	2				1		1	1			7
9.4				1				1		1	1	1	2		7
9.5				1					1						2
9.6															0
9.7							1	1							2
9.8										1					1
9.9								1							1
10.2									1						1
11.9										1					1
Total	53	141	187	155	126	189	179	158	150	191	180	154	172	137	2172
Mean length	8.0	8.0	8.0	8.2	8.0	7.9	8.1	8.2	8.2	8.0	8.2	8.2	7.9	8.1	8.1
P.E.±	.044	.03	.027	.025	.035	.023	.025	.025	.032	.027	.024	.024	.029	.033	.007

The average length, based on the sample of 2,172 individuals, was 8.1 ± 0.007 cm., which when compared with a mean length of 9.2 cm. (Foerster 1934, p. 5) for yearlings of 1927, indicates that the 1928 migrants were conspicuously shorter. Within the length groups extending 0.5 cm. on either side of the mean it is observed that in 1927 only 53 per cent of the individuals were included while in 1928, 71 per cent fall therein, thus emphasizing that in the latter year less variation in size about the mean length occurred.

TABLE IV. Distribution according to weight to nearest 0.5 gram of samples of yearling migrants of 1928 taken during periods indicated.

Weight grams	April 2 3	4 −11	12 13	14 −16	17 −19	20 −22	23 24	25 26	27 28	29	April 30 to May 1	2 3	4 −6	7 −28	Total
2.5			2					1					4		7
3.0		5	7	1	3	2	0	1	6	6	4	3	14	12	64
3.5	1	10	16	1	6	14	0	3	2	6	3	4	19	5	90
4.0	3	30	26	5	14	33	14	25	26	39	37	23	39	23	337
4.5	5	19	17	14	16	34	9	19	16	24	22	17	29	13	254
5.0	11	39	54	40	38	51	55	63	42	62	62	60	36	34	647
5.5	12	13	23	33	16	29	27	20	17	21	14	20	16	12	273
6.0	8	17	22	36	20	16	43	19	26	26	26	21	11	18	309
6.5	8	7	9	5	6	5	14	0	4	0	9	2	2	8	79
7.0	3	0	6	15	4	3	12	5	5	5	2	3	0	9	72
7.5	1	1	5	1	1	2	1	0	5	1	0	1	1	3	23
8.0	1	0	0	1	2	0	3	0	0	0	1	0	1		9
8.5				1			1			1					3
9.0				2				2	1						5
Total	53	141	187	155	126	189	179	158	150	191	180	154	172	137	2172
Mean weight	5.5	5.0	5.0	5.5	5.0	5.0	5.5	5.0	5.0	4.5	5.0	5.0	4.0	5.0	5.0
P.E.±	.086	.048	.052	.050	.058	.042	.038	.048	.058	.047	.043	.043	.054	.067	.014

For weight, table IV, the same comparisons hold. The mean weight for the migrants of 1928 was 5.0 ± 0.014 grams, whereas in 1927 the weighted mean of all samples was 7.9 grams. Greater concentration about the mean weight was noted in 1928 than in 1927.

In order that the difference in size of yearling migrants of 1927 and 1928 may be more accurately determined and more clearly portrayed, length-weight curves for the two years have been constructed by the method of least squares, using the logarithms of the grouped data weighted by the number of individuals, and are shown in figure 1. To illustrate the differences between the curves, the mean lengths and weights, the slope of the curve (b) and the point of its intersection (a) in the equation $y = ax^b$ are given, together with a condition factor devised

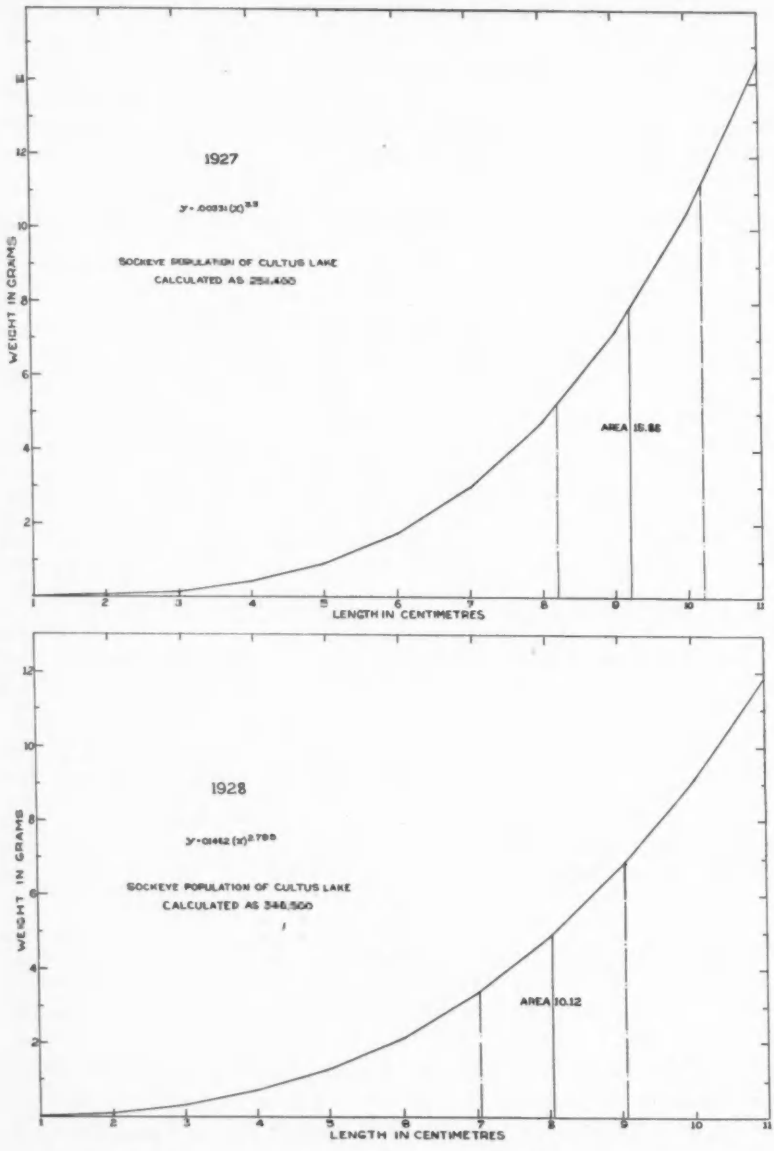


FIGURE 1. Length-weight curves for 1927 and 1928 one-year sockeye migrants. The area under the curve extending one centimetre on either side of the mean length has been selected as the condition-factor of the year's migrants.

to evaluate the general size of the fish in each year's migration. It denotes the area under the curve extending from 1 cm. below the mean length to 1 cm. above it.

Year	Mean length	Mean weight	Equation $y = ax^b$	Migrant sockeye condition factor (one year fish only)
1927	9.2	8.43	$y = .00331\ (x)^{3.5}$	15.86
1928	8.06	5.04	$y = .01462\ (x)^{2.795}$	10.12

RATE OF GROWTH OF YEARLING MIGRANTS.

In the report dealing with the migrants of 1927, no. 3 of this series (Foerster 1929c), the amount of growth experienced by the migrants during their first year and in their second year up to the time of migration, as indicated by the scales from sample individuals, was computed. The length increase for each period was obtained by measuring by camera lucida the width of each year band. A fry length of approximately 38 mm. having been found to coincide with the appearance of the first scale ring, the scale measurements were transformed into millimetres of length increment for the fish by deducting 38 mm. from the total length of the fish and dividing the resulting length in the same proportion as the scale measurements. At the same time counts of scale rings for each period were made. Figures were constructed to present graphically the length increment during the first year and for that portion of the second year up to the time of migration, and it was stated that "it would seem, then, that variations occurring in length at time of collection were due in the first instance to increased growth during the first year and in the second place to increase of growth during the first stages of the second year . . . . . Within limits, the longer the length at the end of the first year, the more rapid the growth during the second year."

A plot of the 1928 data substantiates generally the first statement above with reference to variation and the larger sample dealt with smooths out the extremes indicated in the 1927 data.

The conclusions reached for 1927 concerning the relation between the growth in the two years are, however, quite contradicted by the 1928 data. When the scale measurements were being made it became evident that in nearly all cases where, for a length group, the first year band width was below average that for the second year would be correspondingly greater, as if the fish were tending to compensate during the second season for the slower growth in the initial year. For example, in the 8.0 cm. length group, where the mean scale measurements were found to be 35 and 5 mm., one individual exhibiting a first year scale band width of 19 mm. showed 23 mm. for the second. The measurements of another were 23 and 16 mm., while a third specimen showed a development of 50 and 2 mm. Table V portrays this tendency through the gradual concentration of entries to the left as the width of the first year band increases and is quite the reverse of the 1927 findings.

The purpose of this study at the present time being not so much to evaluate the growth rate for individuals as to obtain a measure of the average development

TABLE V. Frequency table of width of scale year bands of 1928 yearling sockeye for complete first year and portion of second year up to time of migration, in mm. Measured by camera lucida, magnification 110X.

Scale growth first year	Scale growth in second year																								Total
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	21	23	24	25	
12							1	1	0	0	0	1													3
14								1	0	0	0	1													2
18							1	0	0	0	0	1													2
19							1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1			4
20				1	0	1	1	0	0	0	0	0	0	0	1										4
21						2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1				5
22						1	0	1	1	0	0	2	2	2	0	0	1	1							11
23				1	0	1	0	2	0	1	0	1	0	1	0	0	1	0	0	1	0	0	0	1	10
24	1	0	0	0	0	1	1	2	0	3	0	4													12
25		3	2	0	2	0	1	2	1	0	0	2	0	0	1										14
26				4	1	0	0	1	0	3	0	1	1	1	0	0	0	0	0	1					13
27	2	3	1	2	1	0	1	1	0	0	1	0	0	0	0	0	1								13
28		2	0	3	3	2	1	1	3	1	1	0	1										1		19
29	1	4	1	0	1	2	2	2	1	0	1	1	0	1											17
30	3	1	3	0	1	1	1	2	2	1	2	1													18
31	3	3	1	4	0	1	1	7	0	1	1	0	2	0	1	1									26
32	2	3	6	2	5	4	0	4	5	3															34
33	1	1	3	2	1	2	1	4	3	2	2	0	0	0	0	0	1								23
34	1	3	4	1	1	4	5	5	0	1	0	1	1												27
35	2	1	5	2	3	3	2	2	1	2	0	0	2												25
36	4	2	2	3	4	0	4	1	1	2	2	1	1	1	1										29
37	3	4	4	4	0	3	2	3	2	1															26
38	5	2	3	1	0	2	0	3	2	0	1	1													20
39	5	2	3	4	1	0	0	0	2	2	0	2													21
40	3	5	6	4	1	1	0	3	2	1	3	0	1	0	0	1									31
41	3	3	1	2	1	1	2	1	1	2	0	1													18
42	3	1	4	3	1	2	2	2	1																19
43	2	2	9	2	3	3	2	0	0	2	1	0	0	1	1										28
44	4	1	4	1	0	2	0	1																	13
45	5	1	2	1	2	2	0	1																	14
46		3	1	0	1	0	0	0	1	0	0	0	0	1											7
47		1	1	3	0	1	0	1	0	1	0	1													9
48		1																							1
49		1																							1
50	2	2	2	0	0	1																			7
51			1	1	0	0	1																		3
52	1	0	1																						2
53			3																						3
54		1	1																						2
55			1																						1
56		1	0	1																					2
57		1																							1
58				1																					1
59					1																				1
60			1																						1
	56	58	76	53	34	43	33	54	31	29	15	24	11	8	5	2	4	1	0	2	1	1	1	1	543

for the group, no particular attention has been given to an analysis of length increments for individuals or individual length groups. On the other hand, as displayed in table V, actual measurements of the widths of the two scale areas as magnified by camera lucida 110X have been tabulated in the form of a frequency table to show the amount and extent of variation and to calculate a mean for the season. While it is fully realized that the growth of the fish is not directly proportional to the growth of the scale it seems quite satisfactory, in view of the extensive variation and of the fact that no measure of the variation in the length of the fry at the time of the formation of the first ring has been made, to use this calculation as an indicator of sockeye development and eventually to calculate the probable average growth from the means obtained from the frequency table.

From table V, where the variations in millimetres of the width of the first full year (from the first scale ring to the outer margin of the first winter check) and the second partial year are tabulated, it is seen that, for the 543 individuals examined, ranging in length from 6.7 cm. to 10.2 cm., with a mean length of 8.1 cm., the width of the first year band varies from 12 to 60 mm., approximately fifty per cent of the samples lie between 31 and 40 mm. and the mean value is 35 ± 0.23 cm. For the second year's increment the range lies from zero growth to 25 mm., 75 per cent of the samples show from 0 to 7 mm. increase and the mean value is 5 ± 0.12 mm.

Utilizing the mean scale increment measurements as a means of computing the mean length increase of the 1928 yearling migrants it is found that the widths, 35 mm. and 5 mm., produce the following length increments:

Length of fry when first scale ring is formed	38. mm.
Length increment to the end of the first winter	37.5 mm.
Length increment from the end of the first winter to time of migration	5.5 mm.
Total mean length of 1928 yearling migrant	81.0 mm.

The scale ring count is of considerable value as indicating the relative development of young sockeye during their residence in Cultus lake. Appreciable variation occurs, similar to the widths of the scale bands mentioned above, but here again the counts representative of average growth merit attention. In table VI the data for the sample of the 1928 migration are presented. For the first year the mean scale ring count is 14 ± 0.064 and approximately 83 per cent of the individuals are found within the 11 to 16 ring limits. For the second year up to the time of migration the mean count is 1 ± 0.034 with approximately 82 per cent of the specimens possessing from 0 to 2 rings. The tendency for scales exhibiting a low ring count in the first year to have a larger number in the second than those with a high first year count is again apparent. Scale ring counts in almost all cases correspond closely with the peculiarities of the scale in respect of width of year bands and in the examples cited in the preceding paragraphs, of the 8.0 cm. length group, the individuals had scale ring counts as follows:

Width of year bands		Scale ring counts	
First	Second	First year	Second year
19	23	8	8
23	16	9	7
50	2	16	0

The number of scale rings constituting the nucleus or early fresh-water area of the sockeye salmon scale has frequently been considered of value as a means of distinguishing populations from different spawning areas of British Columbia. Sockeye salmon spend normally at least one year in fresh water, in lakes having presumably individual limnobiological peculiarities. These latter would tend to

TABLE VI. Frequency table of scale rings counted in first year band and in that portion of second year up to time of migration for yearling sockeye migrants of 1928.

Number of scale rings	Number of scale rings in second year										
first year	0	1	2	3	4	5	6	7	8	9	Total
6			1	1							2
7					2						2
8		1	1	2	2	0	2	0	1		9
9	1	0	4	1	3	4	1	3	1	1	19
10			6	4	2	3					15
11	7	3	14	15	0	1	1				41
12	22	9	23	10	5	1					70
13	30	14	37	10	3						94
14	47	19	22	9	2	1	1				101
15	49	14	23	3	1	1					91
16	36	15	10	1							62
17	21	3	3								27
18	7	0	1	1							9
19	3										3
20	2										2
	225	78	145	57	20	11	5	3	2	1	547

Mean rings—first year— $14 \pm .064$
second year—$1 \pm .034$

affect the growth of the young fish resident therein and would be impressed upon the scale development for that period. It has been suggested, therefore, that peculiar scale nucleus patterns, such as certain scale ring counts, may assist in the separation of adult populations according to area of spawning. A system of this type may be found practicable but it is here emphasized that in dealing with scale ring counts the variability of the counts in any one season must be recognized and, furthermore, the changes in counts from year to year in the same area, reflecting differences in growth as determined by differing limnobiological conditions in the lake or by the size of the population, may well be such as to render extremely doubtful any general separation unless the scale pattern for each year, noting the peculiar characteristics of that year, is known for each group or area under consideration.

TWO YEAR OLD MIGRANTS.

These individuals, produced from the 1926-27 spawning and spending two years in Cultus lake before migrating seaward, were included in the 1929 downstream migration. From the sample of 4,792 individuals taken at regular intervals throughout the migration which totalled 2,465,000 migrants, it was found that of the first portion of the run, April 3 to 19, when one sample was to be preserved for each 100 migrants counted, 179 individuals were preserved and 23,065 counted. Of the 179 in the sample, 21 were found to be two-year-old fish and it was presumed that, on the basis of the same proportion, approximately 2,700 two-year-olds were contained in the migration of that period. After April 19, with a much larger number of daily migrants running, it became necessary to reduce the sampling to one for each 500 migrants and of the 4,613 sample individuals taken in this manner from the 2,441,300 migrants, 10 were two-year-olds. The total of this age class for the period considered was computed to be 5,300.

The total two-year-old migrants of the 1929 migration amounted, thus, to 8,000 representing *0.09 per cent of the total available eggs and 0.1 per cent of the eggs available for stripping.* Following the method used above for calculating statistical limits of occurrence, those for the two-year-old migrants of the April 3 to 19 group, from a sample of 21 in 179, will be from 1,417 to 4,626 and for the second group, from a sample of 10 in 4,613, from 1,954 to 11,251. If, for the two groups, lower and upper limits be added together, producing totals of 2,371 and 15,877 respectively, *the percentage survival, based on total available eggs, will be between 0.04 and 0.18 per cent, the most probable value being 0.09, and, for eggs available for stripping between 0.04 and 0.2 per cent, the most probable value being 0.1.*

Concerning the relative time of migration of two-year-old individuals it has already been stated that the sample taken for the period April 3 to 19 contained 21. Ten were obtained in subsequent samples up to April 30 but none was encountered after the latter date. The early-running characteristic of two year migrants is thus exemplified.

In table VII are given the data regarding length and weight for 30 of the sample fish and it is observed that the mean lengths and weights, 11.8 cm. and 12.6 grams respectively, are less than those for the 1928 individuals (Foerster 1934) whose means were 12.4 cm. and 18.4 grams. Thus the two-year fish, on the basis of the small sample available, exhibited differences in size in comparison with the previous year's specimens in the same direction as the yearlings, namely an appreciably smaller size.

GROWTH OF TWO YEAR OLD MIGRANTS.

As with the yearling samples, the scales were read, width increments measured by camera lucida and scale rings counted as set down in table VII. On the basis of the mean measurements obtained for each year, namely, 8.4 mm. for the first, 16.1 mm. for the second and 0.0 mm. for that portion of the third year up to time of migration, the mean length increments of a two-year-old migrant 11.8 cm. long

may be calculated as in the following tabulation where comparison is made with yearling migrants of 1928 which were the product of the same brood year:

	Two-year-old migrants		Yearling migrants	
	Length increment	Scale rings	Length increment	Scale rings
To the fry stage	3.8 cm.	1	3.8 cm.	1
During first year	2.6	8.6	3.75	14
During second year	5.4	14.2	.55	1
During third year up to time of migration	0.0	0.0		
	11.8 cm.	23.8	8.1	16

TABLE VII. Data respecting the two-year-old migrants of 1929. Width of yearly scale bands given in mm. as measured by camera lucida under magnification of 110X.

Coll. no.	Length cm.	Weight grams	Width of yearly scale bands			Number of scale rings per year		
			1	2	3	1	2	3
2980	9.8	7.2	8	12	0	8	11	0
3748	10.4	8.5	6	15	0	7	13	0
3517	10.6	9.8	8	19	0	7	15	0
3753	10.7	9.0	6	15	0	7	13	0
2599	10.8	10.0	8	14	0	10	10	0
3705	11.0	10.0	10	13	0	7	15	0
3726	11.0	11.8	8	17	0	7	15	0
3840	11.1	9.5	7	14	0	9	13	0
3230	11.2	9.0	10	14	0	9	12	0
3736	11.2	10.0	7	16	0	7	13	0
3831	11.2	11.0	7	14	0	9	12	0
3782	11.3	9.5	8	17	0	9	14	0
3842	11.3	11.0	6	20	0	6	16	0
3805	11.3	11.5	9	14	0	10	11	0
3780	11.5	12.0	7	17	0	8	14	0
3745	11.6	11.7	8	17	0	8	16	0
3778	11.6	12.2	9	17	0	9	14	0
3260	11.7	11.0	9	16	0	9	11	0
3691	11.8	10.5	8	18	0	8	18	0
3816	12.0	13.5	11	18	0	11	17	0
3811	12.2	12.8	6	16	0	8	15	0
3812	12.2	13.9	10	15	0	10	13	0
3690	12.3	15.5	6	18	0	6	17	0
3784	12.4	13.5	12	16	0	12	13	0
3765	12.4	14.0	6	20	0	6	20	0
2570	12.9	18.0	10	16	0	10	14	0
3804	13.0	16.0	7	15	0	9	13	0
2569	13.1	18.2	13	17	0	10	14	0
1343	14.5	23.0	11	17	4	12	14	3
2568	14.7	25.5	11	16	0	10	19	0
Mean values—	11.8	12.6	8.4	16.1	0	8.6	14.2	0

It is at once evident that the two-year-old sockeye exhibit a different rate of growth to the one-year individuals. In the discussion of the two-year migrants of 1928 (no. 3 of this series, Foerster 1929c) it was pointed out that the two-year-old specimens appeared to experience a smaller increase in length during the first year than the yearlings and the phenomenon is again brought out in the 1929 data. The scale ring counts corroborate this finding. During their second year in the lake, however, growth is rapid and at time of migration the two-year-olds are substantially larger than the majority of the yearlings. In figure 2 the difference in annual length increase between yearlings and two-year-old migrants is diagrammatically portrayed. It is worthy of note that of the 1929 sample only one two-year-old individual displayed third year development. None of the others exhibited on their

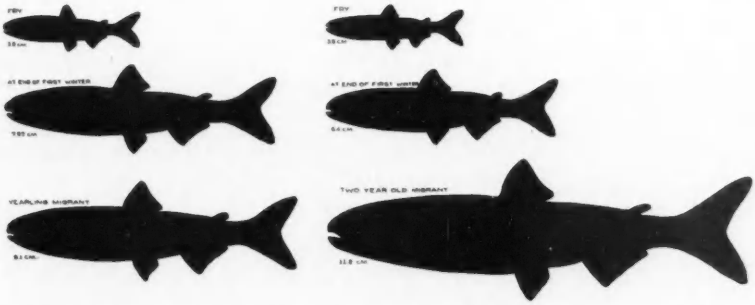


FIGURE 2. Block figures showing the general size attained by young sockeye at stated periods of their fresh-water residence in Cultus lake, as deduced from scale readings of the 1928 one-year and 1929 two-year-old migrants.

scales a commencement of the third summer band outside the second winter check. Comparison of the past three years' samples of two-year-old migrants is shown in the following tabulation:

Year	Number in sample	Mean length cm.	Mean weight grams	Length increments, mm.			Scale ring counts		
				First year	Second year	Third year	First year	Second year	Third year
1927	74	12.4	19.0	20.0	60.0	5.7	6.5	16.0	1.0
1928	12	12.4	18.4	30.6	53.2	2.3	11.8	15.2	0.4
1929	30	11.8	12.6	26.0	54.0	0.0	8.6	14.2	0.0

RETURNING ADULTS

The fry, yearling and two-year-old migrants from Cultus lake may produce adults comprising a number of age groups. Thus far the fry have failed to provide returning adults but the yearlings have been recovered returning as three (3_2), four (4_2) and five-year-olds (5_2). The two-year migrants have produced five-year-olds (5_3). If the returns from the sea for each individual brood year are to be com-

puted, then, it becomes necessary to determine the numbers of fish belonging to each of these age groups in the several spawning runs.

From the propagational measures carried out in 1926-27, and the subsequent seaward migrations of yearlings (1928) and two-year-olds (1929) individuals maturing in their third year (3_2) were expected in 1929, four year fish (4_2) in 1930 and five-year-olds (5_2 and 5_3) in 1931.

As explained in the preceding report, no. 4 of this series (Foerster 1934), samples of the adults migrating to Cultus lake each year were taken at the counting weir and from these an effort made to determine the composition of the run according to age. The scales, by the time the adults reach Cultus lake, are badly absorbed and only in relatively few cases can complete readings be made. The nucleus and generally the first year in the sea are entire and consequently it is possible to separate adults having spent one or two years in fresh water, viz. 4_2 or 5_2 from 5_3, but the distinguishing of 4_2 from 5_2 depends wholly on the condition of the outer area of the scale. Three year adults, 3_2, are usually conspicuous by their much smaller size but in some overlapping cases their identity remains undisclosed.

In spite of the care taken in collecting a proper random sample of each year's adult run, therefore, the actual sample used in determining the age composition depends on the number of readable scales and may hence be reduced to a small number, the adequacy of which, as representing a random sample, may be questioned. There is at present no means of overcoming this difficulty particularly for the 5_2 group but for the 3_2 class consideration of the length frequency distribution may be a valuable aid. While the calculations made for each year group on the basis of the actual sampling are adopted as the most probable values, an effort has been made to define the fiducial limits of such groups in order that the limits of error due to the sampling may be more or less circumscribed. In this respect the confidence coefficient of 0.95 is deemed sufficiently accurate for the purpose.

Of the adults, then, produced from the spawning run of 1926-27 and the subsequent down-stream migrations of 1928 (one-year-old migrants) and 1929 (two-year migrants) there returned to Cultus lake the following:

THREE YEAR ADULTS.

From the 1929 run of 1,645 males and 3,437 females a sample collection of 181 males and 157 females included one three year male and no females. *The most probable number of males would thus be 9 with limits of from 1 to 51. The most probable number of females would be zero, with limits of from 0 to 81.*

FOUR YEAR ADULTS.

The 1930 run of sockeye consisted of 4,856 males and 5,553 females. A sample collection of 11 males and 122 females with readable scales was obtained but in view of the fact that no three year males were included in the sample, though from the length measurements it was obvious that the run contained a fair proportion, the sample is not considered satisfactory.

The length frequencies of the 1930 sample were as follows, lengths being given in cm. (originally in quarter-inch groups):

Length	43.8	44.5	45.1	45.7	46.4	47.0	47.6	48.3	48.9	49.5	50.2	50.8	51.4	52.1	52.7
No. of ♂♂	1	1	4	2	3	3	6	5	8	9	9	25	16	13	6
No. of ♀♀	0	0	0	0	1	1	0	1	0	0	0	0	0	0	1

Length	53.3	54.0	54.6	55.2	55.9	56.5	57.2	57.8	58.4	59.1	59.7	60.3	61.0	61.6	62.2
No. of ♂♂	6	3	2	0	4	1	0	1	0	3	2	5	12	1	13
No. of ♀♀	1	4	2	1	5	9	28	20	56	60	67	60	102	69	47

Length	62.9	63.5	64.1	64.8	65.4	66.0	66.7	67.3	67.9	68.6	69.2	69.9	70.5	71.1
No. of ♂♂	19	23	22	26	32	21	14	13	13	7	1	2	1	1
No. of ♀♀	21	21	4	4	4	2	1	0	0	0	0	0	0	0

The probable occurrence of two age-groups in the length frequency is apparent and for purposes of calculation the 122 males lying in the 43.8 to 54.6 cm. range and the three females at the lower end are considered as three-year-olds. These individuals belonging to the 1927 spawning, are excluded from further consideration. There remain 237 males and 589 females which the 11 males and 122 females in the original scale sample are taken to represent. Of the 11 males 8 were 4_2 and 3 were 5_3. Therefore, in the whole sample of 237 males, the 4_2 group would comprise 172 individuals with limits from 67 to 230 and *of the total run of 4,856 males,* based on the total sample of 359 individuals, *from 906 to 3,111 belonged to the 4_2 group, with the most probable number approximating 2,327.* For the females the 122 individuals in the scale sample consisted of 117 four-year and 5 five-year fish. Therefore in the whole sample of 589 females the 4_2 group would comprise from 533 to 581 individuals with the most probable number being 565 and *for the entire 1930 run of 5,553 females those constituting the 4_2 group would number from 5,000 to 5,450 with the most probable value 5,300.*

FIVE YEAR ADULTS.

These individuals constituted a part of the 1931 run of 10,368 males and 27,105 females. A sample of 237 individuals examined from the total run, 55 males and 182 females, indicated no five-year males and only one five-year, 5_2 female. On such basis *the numbers of the 5_2 group in the 1931 run would be represented as: probable number of males—none, with limits of confidence of from 0 to 698: probable number of females—149, with limits of confidence of from 15 to 834.*

Summarizing the returns of adult fish, produced from the 1926-27 spawning, the following data have been obtained:

Age	Males		Females	
	Probable number	Fiducial limits	Probable number	Fiducial limits
3 year (1929).....	9	1- 50	0	0- 81
4 year (1930).....	2327	906-3111	5300	5000-5450
5 year (1931).....	0	0- 698	149	15- 843
	2336		5449	

The total adults so derived constitute 0.09 per cent of the total available eggs in 1926, 1.02 per cent of eggs available for stripping and 2.3 per cent of the total 344,173 seaward migrants. Similar records for the preceding cycle, 1925-30, showed a return of 5,575 adults or 0.03 per cent of the 17,470,000 eggs available for natural deposition and 3.0 per cent of the total 184,994 seaward migrants.

MARKING EXPERIMENTS

As in the previous year, 1927, (Foerster 1934), of the down-stream migrants of 1928, 99,700 individuals or 29.7 per cent were marked by the removal of the two pelvic fins and the posterior half of the dorsal fin, the purpose being to determine the percentage return of adults from a known escapement of seaward migrants. The fish so handled were liberated immediately after marking to continue down-stream with the unmarked ones.

As the migrants were marked irrespective of age, both one and two-year fish may have been handled and accordingly returns of marked adults were expected as follows: 3_2 in 1929, 4_2 and 5_3 in 1930 and 5_2 in 1931. During these years an endeavour was made to recover marked adults both in the fishing area and at Cultus lake and the results are recorded below.

Return of Marked Fish to Cultus Lake.

No marked three-year-old adults were recovered in 1929 and no five-year marked individuals in 1931 so that the recoveries during the fall of 1930, 548 males and 792 females, constituted the sole return to the spawning grounds, representing 1.34 per cent of the total marked migrants. Such percentage constitutes that portion of the marked migrants which survived to the adult stage and escaped the fishing gear. It differs appreciably from the percentage derived in the section above for returning adults, irrespective of marking, from the 1926-27 spawning, namely 2.3 per cent and no clear explanation for the discrepancy can be given at the present time.

In the preceding report for the 1925-30 cycle, no. 4 of this series, (Foerster 1934), a comparison was made between percentage return of marked adults from marked migrants (0.88 per cent) and return of unmarked adults from the unmarked portion of the 1927, down-stream migration (2.49 per cent). Similar calculations for the 1928 unmarked migrants would indicate, from a return of 9 3_2's in 1929, 7,627 4_2's in 1930, 1,104 5_3's in 1930 and 149 5_2's in 1931 or a total of 8,889 adults, a recovery of 8,889–1,340 or 7,549 unmarked adults representing a percentage recovery of 3.2. Admittedly the data for unmarked adults is susceptible to sampling errors, etc., but it is noteworthy that the differences between returns from marked and from unmarked sockeye migrants in the two years' experiments are of approximately the same order, being $\frac{0.88}{2.49}$ or 0.35 for the 1927 migrants and $\frac{1.34}{3.2}$ or 0.42 for those of 1928. Consideration of this discrepancy will be reserved until the data, shortly to be presented, for years when the entire down-stream migrants were marked, are completed.

TABLE VIII. List of marked adult sockeye recoveries from the fishing areas in 1930, grouped according to date of recovery, age and place of capture.

Date 1930	Number of fish	Age 4_2	Age 5_3	Age 5_2	Location of capture
May 29	1	1			Cherry point
June 6	1	1			Cherry point
July 25	41	35	0	6	Lummi island
July 28-31	7	5		2	Whidby island
	30	26		4	Lummi island and gulf
Aug. 4-11	3	2		1	Whidby island
	2	2			Cherry point
	14	13		1	Lummi island and gulf
	7	6	1	0	Point Roberts
Aug. 12-19	3	2	0	1	Whidby island
	3	3			Cherry point
	36	33	3		Lummi island and gulf
	9	7	2		Point Roberts
	1	1			Fraser river
Aug. 20-27	1	1			Sooke, Vancouver I.
	7	7			Cherry point
	22	20	2		Lummi island and gulf
	7	7			Point Roberts
Aug. 28 to Sept. 4	3	3			Sooke
	6	6			Salmon banks
	3	3			Cherry point
	22	21	1		Lummi island and gulf
	5	5			Boundary bay
	19	19			Point Roberts
	2	2			Johnstone strait
Sept. 5-12	3	3			Sooke
	3	3			Whidby island
	3	3			Cherry point
	8	8			Lummi island
	11	11			Point Roberts
Sept. 13-20	2	2			Sooke
	1	1			Lummi island
	7	7			Point Roberts
Sept. 21-29	1	1			Whidby island
	8	8			Lummi island
	18	18			Point Roberts
Oct. 1- 4	23	23			Lummi island
	3	3			Point Roberts
Oct. 14	6	6			Point Roberts
Nov. 13	2	2			Fraser river
Nov. 14	1	1			Fraser river
Nov. 22	1	1			Fraser river
	356	332	9	15	

Recovery of Marked Sockeye in the Fishing Areas.

As in previous years efforts were made to have marked sockeye taken by commercial gear noted and recorded. Placards advising of the return of marked groups of sockeye, soliciting cooperation and offering a reward for receipt of scars from marked fish together with certain desired data were posted in canneries and fishing camps throughout the area. As a result 341 recoveries were made, all in 1930, of which 332 were of the 4_2 group and 9 were 5_3 individuals. The data pertaining to individual recoveries are given in table VIII and may be grouped into regions of capture as follows:

Strait of Juan de Fuca	J. H. Todd & Sons		9
Salmon banks	Friday Harbor Canning Co.	2	
	Bellingham Canning Co.	4	6
Whidby island	Pacific American Fisheries		13
Cherry point	Pacific American Fisheries		20
Lummi island	Pacific American Fisheries		194
Boundary bay	Bellingham Canning Co.		5
Point Roberts	Bellingham Canning Co.	12	
	Pacific American Fisheries	75	87
Johnstone strait	Quathiaski Canning Co.		2
Fraser river	Canadian Fishing Co.		5
			341

The valuable assistance given by the commercial firms listed above is gratefully acknowledged.

Though these recoveries of 1930 are twice as numerous as those of the previous experiment (Foerster 1934), the returns from the fishing areas do not represent a complete record of all marked fish occurring in the catches of sockeye during the 1930 season. For the third consecutive year this method of collecting marked fish has been adopted and it has failed to bring together the data in adequate numbers. In spite of efforts made to encourage cooperation of fishermen and cannery employees, despite the attraction of a substantial reward (fifty cents per scar), conditions particularly during the peak of the commercial catch were such that but few recoveries were reported, and it is therefore felt that further collection of data in this way is not warranted.

Though the numbers of marked adults taken in the fishing areas cannot be deemed of significance as far as percentage recovery is concerned, certain facts may be noted. Again the Cultus lake sockeye passed through the fishing areas during the main part of the season, mid-July to the end of September, and thus did not represent, as had been previously supposed by certain authorities, a late run entering the fishing areas after most of the fishery operations had ceased. Three individuals were recovered from the Fraser as late as November but these were likely late stragglers. Their scales were largely absorbed. Two marked sockeye were taken in Johnstone strait thus indicating, as did the 4 marked in-

dividuals in the preceding year, that a portion of the Cultus lake run may reach the Fraser river by the northern route.

SUMMARY

The adult sockeye run to Cultus lake in the fall of 1926 totalled 5,071, of which 3,122 were males and 1,949 females. The proportion of the sexes, 8 males to 5 females, differed substantially from that of the previous year, 2 males to 5 females, and resulted from an unusual run of small, precocious three-year males.

Artificial propagation with liberation of free-swimming fry was to be tested and accordingly all sockeye were held below the counting and spawning weir for subsequent stripping. On the basis of 4,500 eggs per female the stripping and hatchery operations may be listed as:

		Percentage of total eggs	Percentage of eggs available for stripping
Total eggs available, 1949 x 4500—	8,770,000	100.0	
Eggs lost in dead females, 261 x 4500—	1,174,000	13.4	
Eggs available for stripping, 1688 x 4500—	7,596,000	86.6	100.0
Eggs lost in stripping operations—	1,109,000	12.6	14.6
Total eggs collected—	6,487,000	74.0	85.4
Hatchery losses—	570,500	6.5	7.5
Total fry available for liberation—	5,916,500	67.5	77.9

As a result of the propagational effort 5,916,500 fry were obtained for liberation into Cultus lake, representing 67.5 per cent of the total eggs available and 77.9 per cent of eggs available for stripping. In the latter computation, eggs lost through females dying during retention or from stripping operations are not included and therefore the true value for hatchery efficiency lies somewhere between the two percentages.

Resulting from the liberation of 5,916,500 fry in Cultus lake in the spring of 1927 there occurred a seaward migration in the spring of 1928, March 19 to June 11, of 336,173 yearlings and, in the spring of 1929, 8,000 two-year-old individuals, *a total of 344,173 migrants or 3.9 per cent of total available eggs and 4.5 per cent of eggs available for stripping.* These percentages are taken to indicate generally the degree of efficiency of the method of artificial propagation involving liberation of free-swimming fry. The total migrants further represent a survival of 5.8 per cent of the 5,916,000 fry liberated in the lake the previous spring.

The size trends of the yearling migrants of 1928 indicate an appreciable reduction in comparison with the 1927 migrants, the average length being 8.1 ± 0.007 cm. average weight, 5.0 ± 0.014 grams, as compared with 9.2 cm. and 7.9 grams for the 1927 individuals. Curves demonstrating the length-weight relationships for the two years are shown and a condition factor, represented by the area under the curve bounded by one cm. on either side of the mean length, utilized.

The rate of growth of the 1928 migrants expressed as the length increment (1) to the end of the first year and (2) to the time of migration, was obtained by

measuring the width of each scale band under magnification of 110X, entering the measurements on a frequency chart and from the mean widths so obtained, computing the average length increase. The mean width (110X) of the first year band was found to be 35±0.23 mm. and that (110X) for the second year up to time of migration, 5±0.12 mm. For a migrant of mean length of 8.1 cm., therefore, the length increments were calculated as 3.8 cm. to time of formation of first ring (fry stage), 3.75 cm. to end of the first year (yearling stage), and 0.55 cm. from the end of the first winter to the time of collection (yearling migrant stage). Scale ring counts for both periods of development were also made and tabulated in frequency tables, the mean counts being 14±0.064 for the first year and 1±0.034 for the second year up to time of collection. A considerable degree of variation existed in the scale ring counts, sufficient, it is felt, to render difficult, because of overlapping, any means of distinguishing adult sockeye from particular spawning areas by characteristic first year ring counts.

Examination of the 31 samples of the two-year-old migrants of 1929 indicated a mean length of 11.8 cm. and a mean weight of 12.6 grams and demonstrated a reduction in size similar to that of the yearlings, in comparison with the two-year individuals of the previous year. Scale readings and application of mean scale measurements to length increase of migrants showed that, on the basis of a fry length of 38 mm. when the first scale ring was formed, the two-year individuals increased 26 mm. during the first year, 54 mm. during the second and no development was displayed in the third year. Scale ring counts of 8.6, 14.2 and 0.0 for first, second and third year up to time of migration respectively were obtained. The two-year migrants again exhibited a smaller length increase during the first year than yearlings present in the lake during the same period and migrating in the spring of 1928.

In an endeavour to compute the number of adult sockeye returning to Cultus lake from the spawning of 1926-27 and the subsequent down-stream migrations of 1928 and 1929, examination of samples from the adult runs to Cultus lake in 1929, 1930 and 1931 was made. Returns were considered to have occurred as follows: 1929 (3-year adults),—9 males and no females; 1930 (4-year-olds),—2,327 males and 5,300 females; 1931 (5-year-olds),—no males and 149 females; a total of 2,336 males and 5,449 females or 7,785 adults, *representing 0.09 per cent of the total available eggs in 1926 and 2.3 per cent of the total seaward migrants.* Because of the difficulty of obtaining an adequate sample of the adult runs an effort has been made to define the limits of confidence for the samples and for their application to each total run by making use of the fiducial limits calculated for Poisson distribution by Ricker.

Of 99,700 down-stream migrants marked in 1928 by removal of both pelvic fins and the posterior half of the dorsal fin there returned to Cultus lake, 1,340 marked adults or 1.34 per cent of the original marking. Of the unmarked portion of the 1928 migration, 236,000 individuals, 7,549 unmarked adults returned, constituting 3.2 per cent of the original unmarked group. The reason for this discrepancy is not yet clear. The return of marked adults to Cultus lake in the 1926-31 cycle, from a known escapement of marked migrants, (1.34 per cent),

was appreciably better than in the 1925-30 cycle just preceding when a recovery of 0.88 per cent was obtained but variation in the amount of such spawning escapement is to be expected, dependent as it is upon the extent of fishing operations off the coast and in the estuary of the Fraser, time of migration of fish through the fishing areas, extent of closed seasons and coincidence of such closed periods with the passage of Cultus lake sockeye through the areas in which fishing is prohibited.

Recoveries of marked Cultus lake sockeye in the fishing areas, a total of 341, while double those of the previous experiment are not considered by any means as representing a complete record of marked fish taken in the fishing areas. While the numbers themselves are of little significance the time of occurrence and place of capture are of interest as confirming previous data indicating that the Cultus lake run does make up a part of the general fishery, not necessarily entering the fishing areas only at the end of the season, and that Cultus lake sockeye reach the Fraser river from both southern (strait of Juan de Fuca) and northern (Johnstone strait) entrances to the strait of Georgia, the former being the much more important route.

REFERENCES

CLOPPER, C. J. and E. S. PEARSON. *Biometrika* **26**, 404-413, 1934.

FOERSTER, R. E. *Contr. Canad. Biol. Fish.*, N.S. **5** (1), 1929a.

Contr. Canad. Biol. Fish., N.S. **5** (2), 1929b.

Contr. Canad. Biol. Fish., N.S. **5** (3), 1929c.

Contr. Canad. Biol. Fish., N.S. **8** (27), 1934.